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SPATIAL REASONING AND UNDERSTANDING THE PARTICULATE NATURE OF MATTER: A MIDDLE SCHOOL PERSPECTIVE

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Education at the University of Kentucky

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ABSTRACT OF DISSERTATION

SPATIAL REASONING AND UNDERSTANDING THE PARTICULATE NATURE OF MATTER: A MIDDLE SCHOOL PERSPECTIVE

This dissertation employed a mixed-methods approach to examine the relationship between spatial reasoning ability and understanding of chemistry content for both middle school students and their science teachers. Spatial reasoning has been linked to success in learning STEM subjects (Wai, Lubinski, & Benbow, 2009). Previous studies have shown a correlation between understanding of chemistry content and spatial reasoning ability (e.g., Pribyl & Bodner, 1987; Wu & Shah, 2003; Stieff, 2013), raising the importance of developing the spatial reasoning ability of both teachers and students. Few studies examine middle school students’ or in-service middle school teachers’ understanding of chemistry concepts or its relation to spatial reasoning ability. The first paper in this dissertation addresses the quantitative relationship between mental rotation, a type of spatial reasoning ability, and understanding a fundamental concept in chemistry, the particulate nature of matter. The data showed a significant, positive correlation between scores on the Purdue Spatial Visualization Test of Rotations (PSVT; Bodner & Guay, 1997) and the Particulate Nature of Matter Assessment (ParNoMA; Yezierski, 2003) for middle school students prior to and after chemistry instruction. A significant difference in spatial ability among students choosing different answer choices on ParNoMA questions was also found. The second paper examined the ways in which students of different spatial abilities talked about matter and chemicals differently. Students with higher spatial ability tended to provide more of an explanation, though not necessarily in an articulate matter. In contrast, lower spatial ability students tended to use any keywords that seemed relevant, but provided little or no explanation. The third paper examined the relationship between mental reasoning and understanding chemistry for middle school science teachers. Similar to their students, a significant, positive correlation between scores on the PSVT and the ParNoMA was observed. Teachers who used consistent reasoning in providing definitions and examples for matter and chemistry tended to have higher spatial abilities than those teachers who used inconsistent reasoning on the same questions. This is the first study to explore the relationship between spatial reasoning and understanding of chemistry concepts at the middle school level. Though we are unable to infer cause and effect relationship from correlational data, these results illustrate a need to further investigate this relationship as well as identify the...
relationship between different spatial abilities (not just mental rotation) and other chemistry concepts.

KEYWORDS: Spatial Reasoning, Particulate Nature of Matter, Middle School, Chemistry, Mental Rotation
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Chapter 1

Problem Statement and Description

Researchers have identified a variety of ways in which chemistry is difficult for many people (e.g. Nakhleh, 1992; Nakhleh et al., 2005; Nicholl, 2001) as well as ways to overcome these common difficulties (e.g. Tsai, 1999; Bridle & Yezierski, 2012;). People of all ages struggle with learning chemistry. This dissertation focuses on relating two pieces that are needed for understanding chemistry – spatial reasoning and content knowledge. Novices rely more on decontextualized spatial abilities than experts do, making spatial reasoning potentially more important at earlier ages than for students later into their studies in chemistry (Uttal & Cohen, 2012).

Wu and Shah (2004) conducted a meta-analysis of “visuospatial thinking” in chemistry concluding among other things that more research is need at the pre-college level. In the context of their work, Wu and Shah, like many other researchers, are referring to the high school level when discussing pre-college chemistry. Within the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), there is plenty of chemistry within the high school grade band’s standards for physical science. Many of these concepts mirror those taught in college level general chemistry, such as intermolecular forces, periodic trends, thermochemistry, and the conservation of matter. If we look closer, we can see that the concepts begin in the 5th grade with one of the most fundamental concepts in chemistry, the particulate nature of matter (NGSS Lead States, 2013). The chemistry content within the NGSS continues in the middle school grade band. You can find the signs of chemical reactions, properties of matter, conservation of matter, thermochemistry, and the composition of molecules. Each of these ideas is
considered at the particulate level as opposed to relying on macroscopic properties or observations as in elementary level standards. If middle school contains these fundamental ideas of chemistry, and spatial reasoning ability is needed for truly understanding chemistry, then why aren’t we exploring the relationships between chemistry content knowledge and spatial ability within middle school classrooms?

The intent of this multiple-manuscript dissertation is to explore contributing factors to students’ understanding of the particulate nature of matter. The particulate nature of matter is a core concept in chemistry. Students are often expected to implicitly apply the particulate nature of matter after being taught about it as a set of facts rather than explicitly exploring the tenets of the particulate nature of matter.

Spatial ability is often cited as a contributing factor in students’ success in chemistry (Gabel, Samuel, & Hunn, 1987; Pribyl & Bodner, 1987; Bodner & Guay, 1997). However, many of these studies are focused at the college level, particularly in organic chemistry. There are some research studies looking at students’ understanding of chemistry at the middle school level, but none to my knowledge that link spatial ability and student understanding of the particulate nature of matter. Studies show that correlations between spatial ability and chemistry ability exist not only for problems that are obviously spatial in nature, such as rotating molecules to identify isomers (molecules that contain the same atoms but in a different arrangement), but also questions that require problem solving skills, such as stoichiometry (Grabow, 2003; Bodner & Guay, 1997; Carter, LaRussa, & Bodner, 1987). Carter et al. (1987) found the correlation with spatial ability was stronger for questions that tested problem solving skills rather than
rote memorization or the use of an algorithm. Bodner and McMillen (1986) also found a statistically significant correlation between spatial ability and chemistry test scores.

While sub-questions are presented with each manuscript, overall, this set of manuscripts seeks to address the research question, *In what ways are spatial reasoning and understanding of chemistry content related in middle school classrooms?*

**Importance of the Problem**

A strong foundation in the fundamental ideas of chemistry, such as the particulate nature of matter, is essential for students to learn chemistry (Gabel et al., 1987). In order to understand how teachers can better create this foundation, it is important to identify contributing factors. The link between spatial ability and chemistry concepts should be explored at the middle school level because that is when students first begin to explore the fundamental ideas of chemistry in their science classrooms. Identifying predictors of success with the concept of the particulate nature of matter provides information for teachers and researchers about the skills and concepts that need to be emphasized in classrooms. The contribution of spatial ability to chemistry and other STEM fields hold true, even when controlling for other relevant abilities (Wai, Lubinski, & Benbow, 2010). Wai, Lubinski, and Benbow (2009) found that students who later earned STEM degrees had significantly higher spatial abilities at age 13 than those who earned degrees in other areas. Also, higher level achievements (e.g. earning a PhD vs a BS) are predicted by greater spatial ability (Kell, Lubinski, Benbow, & Stanley, 2013). Hegarty (2014) noted spatial ability is not emphasized in schools, saying this deficiency, “not only prevents less able students from achievement in science. It also hinders us from identifying and nurturing the talents of our most spatially able students” (p. 143). The goal of this set of
papers is to 1) identify links between spatial reasoning and understanding of the particulate nature of matter, 2) explore how students explicate their mental models of understanding chemistry, and 3) investigate content knowledge and spatial reasoning ability of middle school science teachers. This work will contribute to the education literature by examining connections between spatial reasoning ability and chemistry content knowledge for both middle school students and teachers. While the research on students is important, the paper focusing on teachers is perhaps the most significant because researchers often have to infer teachers’ content knowledge in place of measuring it directly.

The Particulate Nature of Matter

Whether considering Democritus’ view that matter is made up of tiny, indivisible particles that determined the properties of a substance, or Aristotle’s later opposing view that all matter is composed of the four elements, earth, air, fire, and water, philosophers and chemists long debated the composition of matter (Brock, 1992). Democritus’ view of matter required more imagination and abstract thought. There were no tools available in ancient Greece to allow the early natural philosophers to see atoms or to be able to provide empirical evidence to support their ideas. Aristotle’s view of matter could be sensed by humans; they could feel whether something was hot, cold, wet, or dry, making Democritus’ atomism seem to be pure imagination (Brock, 1992). Students likely feel the same disbelief the first time they are told matter is made of tiny particles they cannot see. Rather than dealing with something they can interact with directly, they are being asked to think abstractly about matter and trust the science their teacher is telling them.
Many students have difficulty in understanding matter and its interactions. Students can make observations at the macroscopic level of the properties of matter. They can see things like color, shape, and size. They can also observe changes to each of these through physical or chemical processes. For instance, they can see that an ice cube melts into a puddle of liquid water when left in a warm room. They can also observe the opposite process occur if the liquid is poured into an ice cube tray and placed in the freezer. When students are asked to explain why these changes or properties occur, they run into problems. They can make conjectures about what they think is happening, but unless they understand that matter is made of tiny particles they cannot see and it is the interactions between these particles, they cannot truly explain their observations.

The particulate nature of matter refers to the atomic, molecular, and ionic interactions that result in chemical phenomena (Johnstone, 1991; Gabel, 1999; Bunce & Gabel, 2002). The particulate nature of matter is a concept that states: 1) matter is composed of tiny, individual particles, 2) the particles are always in motion, and 3) the nature of the particles and their interactions define the properties of matter (Nyachwaya, Mohamed, Roehrig, Wood, Kern, & Schneider, 2011). When discussing the importance of the particulate nature of matter, Margel, Eylon, & Scherz (2008) said that understanding the concept of the particulate nature of matter illuminates “relationships between structure, properties, and applications of materials, which will in turn help us understand phenomena in the world around us” (p. 135).

Understanding that matter is made up of particles (i.e. atoms, molecules, and ions) is important in order for students to understand how or why chemistry happens. Smith, Wiser, Anderson, and Krajcik (2006) asserted “understanding the atomic-molecular
theory depends crucially on the macroscopic big ideas studied earlier (e.g., the understanding that matter has weight and occupies space) and, at the same time, it provides deeper explanatory accounts of macroscopic properties and phenomena” (p. 12). If students are unable to envision that matter is composed of tiny particles, they will not be able to understand how these particles interact through chemical reactions or physical processes. Students need to understand that matter is made of particles in order to provide sub-microscopic explanations for macroscopic observations of phenomena. Without it, they are missing a corner of Johnstone’s (1991) triangle. Wright (2003) asserts “when students learn about atoms they are given the key to unlocking many of the doors across the sciences, in physics, chemistry, biology, and earth science” (p. 18). Talanquer (2008) analyzed the research literature on alternative conceptions students hold about the particulate nature of matter. He noted a major transition occurring when students start thinking about matter as composed of particles that have definite attributes.

**Theoretical Perspectives and Related Literature**

Many students struggle with and are unsuccessful in learning chemistry at all grade levels (Nakhleh, 1992). One possible reason is that students fail to understand fundamental concepts, and are unable to build an understanding of more advanced concepts (Gabel, Samuel, & Hunn, 1987). Another possible reason is that understanding chemistry requires the use of multiple levels of description. Johnstone (1991) described this problem; chemistry entails macroscopic and sub-microscopic level understandings as well as a facility with the representations and symbolism used to describe matter and its interactions. To understand chemistry, a person must be able to simultaneously understand the phenomena with which we can directly interact, and the interactions of
particles too small to see. The behavior of these tiny particles explains the macroscopic phenomena we can observe. A person must be able to move freely among the sub-microscopic (i.e. molecular/atomic/subatomic), macroscopic (i.e. what we can easily see with the naked eye), and symbolic (i.e. physical models or drawings of chemical phenomena, symbols, equations) levels of understanding (Johnstone, 1993). While novices are often stuck on one or more edges of the triangle, professionals in chemistry are able to easily operate in this triangle, sliding from area to area and blending areas as necessary.

Johnstone (1993) illustrates the problem of teaching chemistry to beginners by describing a situation where students are shown three piles of powder: carbon, sulfur, and silicon. Each of these are easily identified as an element to a chemist, but to the novice they are piles of black, yellow or brown powder. At the macroscopic level, students can see the colored powder, but would have to assume the sub-microscopic level description of the powders is correct. To complicate matters, Johnstone describes adding three more piles: CuO (copper (II) oxide, a black powder), PbO₂ (lead (IV) oxide, a brown powder), and PbO (lead (II) oxide, a yellow powder). Again, the novice can perceive the macroscopic appearance, but would have to trust the chemist that these powders are compounds rather than elements as before. Johnstone (1993) notes that in “trying to ‘sell’ the concepts of element and compound, we are simultaneously having to ‘sell’ the sub micro concepts of atom and molecule and representing all of this by symbols, formulas, and equations. We are in the middle of the triangle… and few of our students follow us there” easily (p. 704). Johnstone’s triangle is shown in Figure 1.1.
One of the major challenges in learning chemistry is being able to work with all three levels of the triangle - macroscopic, sub-microscopic, and symbolic - at the same time (Johnstone, 1991). Each of these levels plays a role in explaining a phenomenon, and should not be portrayed separately; it is the ability to shift among the three that is required for understanding chemistry (Russell, Kozma, Jones, Wykoff, Marx, & Davis, 1997; Treagust, Chittleborough, & Mamiala, 2003). Researchers have observed that chemistry instruction is mostly at the symbolic level; we rely on the symbols, models, and mathematics of chemistry in classrooms (Gabel, 1999; Johnstone, 1991; Nakhleh, 1993).

Gabel (2005) noted that most chemistry instruction is at the symbolic level, focusing on symbols, equations, and mathematics rather than conceptual understanding. She points out that this is one of the reasons students struggle with chemistry. Gabel (2005) is not saying that the symbolic, mathematics-heavy level is not important, but rather that it should not be the sole focus at the expense of the conceptual understanding that can be gained by also focusing on the macroscopic and particulate levels of chemistry representation.

Hegarty (2010) identified two components of spatial intelligence: flexible strategy
choice and meta-representational competence. Flexible strategy choice involves deciding when to use mental imagery versus analytical thinking. Meta-representational competence refers to the awareness of which is the best representation to use for addressing a specific task and the ability to use the properly chosen representation effectively (diSessa, 2004). This metacognition may be especially important when we consider its relation to Johnstone’s (1991; 1993) triangle. Johnstone noted that novice chemistry students often get stuck at one vertex or along one side of the triangle. They have a difficult time moving to the fluid center of the triangle where the expert resides. One of the issues in doing so lies in understanding and using the many representations and symbols in chemistry; sometimes there are many representations for a single problem (see Figure 1.2).

![Figure 1.2: Different ways to represent ethanol.](image)

Hegarty’s (2010) notion of meta-representational competence may be what separates the novice chemist from the expert. The experts are likely aware of and able to choose the most appropriate representations for the task and use them effectively to address the problem. diSessa (2004) asserts “to the extent that we want to and believe we can help students do the things scientists do, [meta-representational competence], … should be a part of our goals” (p. 296); teaching students this component of spatial intelligence could help them navigate Johnstone’s triangle.
Traditionally, chemistry is taught using a combination of lectures, problem sets, and laboratory exercises. The content is delivered through lecture and practiced in problem sets. Content and laboratory skills are practiced in laboratory experiments, sometimes designed as open-ended inquiry investigations, but often including step-by-step instructions to obtain a known result. Nowhere in this description do we see the three principles Bransford and Donovan (2005) discussed in *How Students Learn*: 1) addressing preconceptions, 2) knowledge of what it means to *do science*, and 3) metacognition. The lectures may go on without taking the time to identify what students already know or the misconceptions they may hold. The cookbook laboratory experiences do not match the way science is done, potentially leading to a misunderstanding of what it means to *do science*. By completing routine problem sets and labs, students do not need to develop any metacognitive awareness of their developing chemistry knowledge. Fortunately, there are suggestions in the science education literature for better ways to teach chemistry.

Gabel (2005) suggests there are two main reasons students struggle with understanding chemistry: 1) most of the instruction is at the symbolic level, assuming students can make their own connections to the macroscopic and sub-microscopic levels, and 2) students have their own conceptions about how the natural world works, including misconceptions about basic chemistry. She discusses the issue that most instruction in chemistry is at the symbolic level, but students need to engage with all three levels – macroscopic, sub-microscopic, and symbolic – to really understand chemistry. Gabel (2005) suggests an alternative to the usual symbolic-heavy lecture method. First, students should observe and describe a familiar chemical reaction in a laboratory setting.
Next, students should provide an explanation for what they just saw at the particulate (sub-microscopic) level. Then, students should represent the reaction symbolically using a balanced chemical reaction. Finally, students should have the opportunity to apply this understanding in a written problem. By starting instruction at the symbolic level, the concepts are less connected to prior experiences and understandings of the student (Gabel, 2005).

Gabel’s (2005) approach could be used for teaching chemistry topics at any grade; it is a reminder for teachers to be cognizant of the three levels of representation in chemistry more than an instructional method. It may need to be modified to fit the grade level. While older students could benefit from starting at the macroscopic level in order to connect new knowledge with existing knowledge, younger students may not be able to move beyond the macroscopic level at first. In early elementary grades, students are asked to focus on macroscopic observations and explanations in the NGSS (NGSS Lead States, 2013). As they progress in age, the standards begin to include sub-microscopic explanations and later, mathematical models and symbolic representations. In this respect, Gabel’s (2005) approach could be applied within a class for older students or over the entire K-12 system.

Middle school standards in the Next Generation Science Standards (NGSS Lead States, 2013) require students to learn concepts in chemistry related to the nature of matter. In learning these concepts, students are expected to move among the three areas on Johnstone’s triangle, often on their own. Learning chemistry entails not only an understanding of what can be seen with the naked eye, but also the ability to visualize things we cannot easily see and an ability to work with symbols or representations of
objects and processes with which we cannot directly interact (Johnstone, 1991; Johnstone, 1993).

**Learning Progressions on Matter**

Learning progressions are “descriptions of successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time” (NRC, 2007, p. 219). Learning progressions are anchored in what students know and understand about concepts at one point, and are anchored at the other end by what they are expected to know at a later point in time. Essentially, a learning progression shows how students can build on early knowledge to construct a framework of understanding for a more complicated scientific idea. A student can move through the learning progression via multiple paths. The particular path followed may be influenced by “prior instructional experiences, individual differences, and current instruction” (Smith, Wiser, Anderson, & Krajcik, 2006, p. 6). The authors also note “actual learning is more like ecological succession, with changes taking place simultaneously in multiple interconnected ways, than like the artificially constrained and ordered accounts” that are described in a learning progression (p. 6). Learning progression research represents a shift in research focus from instruction that focuses on what students know to sequential instruction to develop scientific understanding of a topic (Duschl, Maeng, & Sezen, 2011). For a learning progression to occur, appropriate instructional practices are needed (NRC, 2007).

While there are no learning progressions specifically on the particulate nature of matter learning progressions on the nature of matter in general exist. One of these, by Smith, Wiser, Anderson, Krajcik, & Coppola (2004), focused on the following six ideas:
M1. Macroscopic Properties: We can learn about the objects and materials that constitute the world through measurement, classification, and description according to their properties.

M2. Macroscopic Conservation: Matter can be transformed, but not created or destroyed, through physical and chemical processes.

AM1. Atomic-molecular theory: All matter that we encounter on Earth is made of less than 100 kinds of atoms, which are commonly bonded together in molecules and networks.

AM2. Atomic-molecular explanation of materials: The properties of materials are determined by the nature, arrangement, and motion of the atoms and molecules of which they are made.

AM3. Atomic-molecular explanation of transformations: Changes in matter involve both changes and underlying continuities in atoms and molecules.

AM4. Distinguishing data from atomic-molecular explanations: The properties of and changes in atoms and molecules have to be distinguished from the macroscopic properties and phenomena they account for. (p. 11)

This learning progression starts in early grades and continues through high school chemistry. Regardless of the learning progression followed, it is important to note that not all students make it through the entire progression to fully understand the nature and interactions of matter (Smith et al., 2006). This particular learning progression is useful in that it follows the work of Johnstone (1991, 1993) and Gabel (2005) on the chemistry
Next Generation Science Standards

The Next Generation Science Standards (NGSS; NGSS Lead States, 2013) are designed with the idea that students need to learn more about science than just facts. To address this idea, the NGSS are designed with three dimensions: disciplinary core ideas, crosscutting concepts, and science and engineering practices. When combined with the performance expectations, the NGSS provide standards that relate both what students should know and what they should be able to do. The combination of the performance expectations, crosscutting concepts, and science and engineering practices will allow students to use their science knowledge in meaningful ways (Cooper, 2013). A Framework for K-12 Science Education (NRC, 2012) explains how the Disciplinary Core Ideas should progress through the grade levels, following the research on learning progressions. Each DCI includes an overarching question to guide the progression of ideas.

The NGSS list standards by grade level for K-5th grade and then by grade band for middle school and high school. In addition, they are arranged with a progression of increasingly complex ideas for each Disciplinary Core Idea. The NGSS include these progressions to show endpoints indicating what students should know by the end of grades K-2, 3-5, 6-8, and 9-12. The crosscutting concepts and science and engineering practices are intended to be incorporated and addressed throughout the grades.

Appendix E in the Next Generation Science Standards (NGSS: NGSS Lead States, 2013) describes the progressions of the disciplinary core ideas (DCI) across grade
bands. The most relevant DCI to the particulate nature of matter is PS1.A Structure of Matter, though the concept appears within other DCIs as well, generally as an application of the concept. The progression starts at the K-2 grade band with the idea that matter has properties and that objects can be made from smaller pieces. It doesn’t specify what these smaller pieces are or suggest that they may be too small to see. These ideas appear in the 3-5 grade band, though the idea that matter is made up of tiny particles too small to see (the particulate nature of matter) is only addressed at the 5th grade level. This grade band also adds the idea that the properties of substances that we began to observe in the K-2 level can be used to identify materials.

In the 6-8 grade band, the particulate nature of matter is brought to the forefront: “the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter” (NGSS Lead States, 2013, Appendix E p. 41). This middle school grade band places a heavy emphasis on thinking about matter and its interactions at the particulate level. The high school grade band continues this focus and uses it to explain the chemistry that we see. In particular, there is an emphasis on the electrons within an atom, since that is where much of the chemistry lies. There is also a discussion of nuclear processes in which an atom is broken down into even smaller pieces in order for a nuclear reaction or nuclear process to occur.

While none of the standards specifically ask students to investigate or learn about the particulate nature of matter, many standards either refer to chemical phenomena at the particulate level or provide an application of the particulate nature of matter. The standards related to the particulate nature of matter are discussed in the next three
sections. The full text of the performance expectations relevant to the particulate nature of matter can be found in Appendix A and Appendix B.

**Elementary Level Students**

The first time students are introduced to the idea that matter is made of particles (i.e. the particulate nature of matter) is in fifth grade. Until that point, student investigations of the physical world around them rely on macroscopic observations and explanations. In fifth grade, the NGSS include a performance expectation (PE) that asks students to “develop a model to describe that matter is made of particles too small to be seen” (5-PS1-1; NGSS Lead States, 2013, p. 43). This PE is linked with the crosscutting concept of Scale, Proportion, and Quantity, specifically that “natural objects exist from the very small to the very large” (NGSS Lead States, 2013, p. 43). It is also linked with the Disciplinary Core Idea that discusses the idea that all matter can be subdivided into particles and that models can be created to illustrate the particulate nature of matter (PS1.A; NGSS Lead States, 2013).

**Middle Level Students**

Students begin to really explore the particulate nature of matter in the middle school standards. Within the physical science standards, they are asked to model the changes in particle motion when thermal energy is added or removed (MS-PS1-4), determine whether a chemical reaction has occurred (MS-PS1-2), model the conservation of mass at the atomic level (MS-PS1-5), and to investigate the relationships among energy transferred, matter, mass, and energy of particles (MS-PS3-4). Students are able to apply their emerging understanding of the particulate nature of matter in the life sciences and Earth and space sciences standards. In MS-LS1-6 and MS-LS1-7, students need to
consider how matter moves through organisms and ecosystems; in order to truly address these performance expectations, students need to understand that molecules are broken down, atoms are rearranged, and new bonds are formed. MS-ESS2-4 similarly allows for the application of the particulate nature of matter as it addresses the water cycle. Within the water cycle, molecules of water are changing state; in order to understand changes of state at more than a superficial level, the arrangement of particles within each state should be considered (Johnson, 1998a; Johnson, 1998b).

**High School Level Students**

At the high school level, students are expected to build on the understanding of chemistry at the particulate level they began in middle school. For instance, in HS-PS2-6, students are expected to be able to explain, “why the molecular-level structure is important in the functioning of designed materials” (NGSS Lead States, 2013, p. 94). HS-PS3-2 asks students develop a model to explain the transfer of energy (observed at the macroscopic scale) at the particulate level. Within HS-PS1, Matter and Interactions, the performance expectations ask students to consider a variety of chemistry topics (structure of substances, bond energy, conservation of mass related to conservation of atoms, kinetics, equilibrium, and periodic trends) at the particulate level.

The high school life sciences standards provide opportunities to apply particulate level thinking outside of chemistry. There are standards that address photosynthesis (HS-LS1-5); cycling of carbon, hydrogen, and oxygen in an organism (HS-LS1-6); processing of food in an organism (HS-LS1-7); cycling of matter and energy in an organism (HS-LS2-3) and in an ecosystem (HS-LS2-4); and the carbon cycle (HS-LS2-5).
What do Middle School Students Know About the Particulate Nature of Matter?

Nakhleh conducted a series of studies investigating students’ conceptions of the particulate nature of matter. In a study of fifteen elementary school students (ages 7-10), Nakhleh and Samarapungavan (1999), students’ beliefs about matter were investigated, particularly those related to the states of matter and phase changes. The students’ conceptions of matter were categorized as macrocontinuous (i.e. matter is made of one big piece; no particles are involved), macroparticulate (i.e. matter includes smaller pieces, but description is not of molecules; small pieces are like the pieces that make up a broken object), or microparticulate (i.e. molecular or atomic view of matter; particles are very tiny and cannot be seen with the naked eye). Sixty-percent of the students interviewed expressed views that showed a macroparticulate view of matter, while the rest of the students were split evenly between macrocontinuous and microparticulate descriptions. They also note that children’s conceptions of matter were not consistently developed across the spectrum; some exhibited different views of solids versus liquids or gases. The authors suggest that children’s beliefs about matter are fragmented rather than being part of a true explanatory framework. In addition, children’s views of matter seemed to be more descriptive than explanatory; they viewed macroscopic properties as intrinsic properties of the substance. Nakhleh and Samarapungavan (1999) assert that elementary science instruction should focus on helping children make the transition from macroscopic properties of matter to a particulate description of matter and its interactions.

Nakhleh, Samarapungavan, and Saglam (2005) conducted a study where middle school students’ developing understanding of the nature of matter was studied. Similar to
the study with the elementary students, middle school students were interviewed. The researchers wanted to see how students described solid, liquid, and gas substances, including during changes of state. The students’ responses were again classified as macrocontinuous, macroparticulate, or microparticulate. The researchers found that middle school students are in the process of transitioning to a more scientifically accurate particulate view of matter, but nearly one third of the students continued to hold an inaccurate macroscopic-level view. These findings support both the Next Generation Science Standards (NGSS Lead States, 2013) and the AAA Benchmarks for Science Literacy (AAAS, 2009), which include the particulate nature of matter at the middle school level. However, this is in contrast to the National Science Education Standards (NRC, 1996), which suggest most students won’t be able to understand that matter is composed of atoms and molecules until high school. Gabel, Samuel, and Hunn (1987) commented that the age level when the particulate nature of matter should be introduced to students is questionable. However, they also point out matter is illustrated using particulate level diagrams in many elementary textbooks.

Ben-Zvi, Eylon, and Silberstein (1986) interviewed 10th grade students about their beliefs on matter. They were asked questions about the properties of an atom from copper wire and an atom from the gas formed when copper is vaporized. Nearly half of the students believed the macroscopic properties they could observe of the wire applied to the individual atoms as well, demonstrating a misconception about the nature of matter. Students could use the terms atom and molecule, but struggled to relate them to a particulate view of matter.
The power of chemistry to explain natural phenomena lies at the atomic level (Hesse & Anderson, 1992; Treagust & Chittleborough, 2001), but students are often expected to make the link between the macroscopic observations and the sub-microscopic explanations on their own. Researchers have suggested that instruction is needed at the atomic level in order for students to develop an understanding of chemistry (Ahtee & Varjola, 1998; Gabel, 1993). Similar to Lee et al., (1993), Nakhleh, et al. (2005) also suggest that one reason students struggle to view matter as particulate is that they continue to base their ideas solely on their observations rather than incorporating new abstract information about the particles in matter from their science lessons in school into their framework of understanding about matter.

**Application of the Particulate Nature of Matter in Other Science Courses**

It is important for students to form a good understanding of the particulate nature of matter in middle school because this understanding is needed in order to succeed in other science courses. A common science sequence in high school is Biology in 9th grade, Chemistry in 10th grade, Physics in 11th grade, and an elective or advanced science course in 12th grade. Biology includes many concepts that require an understanding of matter and its interactions at the particulate level. Some of the topics that frequently appear in a biology textbook include “osmosis and diffusion, photosynthesis, cellular respiration, digestion, transpiration, the water cycle, and ecological matter cycling” (Lee et al., 1993, p. 268). Since biology is often taught prior to chemistry in high schools, it is imperative that students gain an understanding of matter and its interactions at the particulate level while in middle school.
Misconceptions in Chemistry

Students bring their own views of science into the classroom. These ideas may be well-established in their own thinking, but do not necessarily agree with the ideas of scientific community. Researchers sometimes refer to these alternate views as misconceptions (Helm, 1980), alternative frameworks (Driver, 1981), or children’s science (Gilbert & Watts, 1982). Nakhleh (1992) noted there are many misconceptions held by students about chemistry. Some of these persist despite instruction in chemistry, sometimes even into graduate level education. She goes on to assert that educators must address this issue, beginning by introducing students to atoms, molecules and ions including when each term is appropriate. Nakhleh (1992) asserted “students should be reminded that if they can’t explain a concept in molecular terms, then they really don’t understand it” (p. 195).

In addition to the developing understanding of matter previously mentioned, Nakhleh, et al. (2005) identified an important misconception held by many middle school students. These students misunderstood the size of atoms, thinking they could be seen under an optical microscope. The authors suggest that this misconception may stem from formal instruction, where students learn that both atoms and microbes are tiny things that cannot be seen with the naked eye. The authors go on to suggest that this description “may have caused them to believe that atoms are similar to microbes, or at least that they are of the same size” (Nakhleh et.al, 2005, p 607). Teachers at all levels need to be careful not to inadvertently introduce new misconceptions. The first step, however, is uncovering what students already know, including any misconceptions they may hold.
Overcoming misconceptions

Misconceptions are often resistant to change; students describe phenomena using their own frameworks that are often well-developed. To overcome students’ misconceptions, the student must encounter an experience that runs counter to their current framework. Then they need to explore and make sense of the new information to devise a new framework. Sometimes this will lead to a new correct conception, but other times it will lead to a different misconception than the student held earlier (Bridle & Yezierski, 2012).

Tsai (1999) investigated using analogies to overcome eighth grade students’ misconceptions about the movement of particles during a phase change. In this study, the experimental group of students participated in an analogy activity where they role-played the movement of particles in phase changes. While no significant difference was found between the control and experimental groups of students on an immediate post-assessment of understanding of the sub-microscopic view of phase changes, students in the experimental group did perform statistically better on a delayed post-test. The delayed post-test performance of the control group showed slightly lower scores than the immediate post-test, but the experimental students showed less regression of understanding, leading to the significant difference between groups.

In a study of sixth-grade students, Lee et al. (1993) administered paper-and-pencil tests and conducted clinical interviews to investigate how students explained the structure of matter and to assess the effectiveness of two alternative curriculum units on the subject of matter. They found that prior to instruction, most students had misconceptions about matter at the macroscopic level, and primarily guessed on questions addressing the sub-
microscopic level. They also found that students had difficulty describing matter in a particulate form, rather describing it from a macro-scale. For instance, students would describe molecules in substances undergoing changes of state as “expanding, contracting, melting, evaporating, and so forth” (Lee et al., 1993, p. 39) rather than explaining how the molecules within the matter moved. Using a targeted curriculum that was designed to address both the macro and sub-micro scales helped compared to a curriculum that focused on scientific facts, but not all students were able to grasp the particulate nature of matter in the end (Lee et al., 1993, p. 39).

Yezierski & Birk (2006) found that students exposed to computer animations of the particulate nature of phases of water and phase changes of water performed significantly better on an assessment of the particulate nature of matter than students who did not use the animations. This study looked at students in middle school, high school, and college chemistry classes. The authors suggest the significant gains can be explained in one of two ways. First, they suggest that since students who are able to visualize the atomic level of chemical phenomena often develop a conceptual understanding of the phenomena, the animations may help these students create mental models of particle behavior. Second, they posit that perhaps a conceptual change has occurred, where the animations may have shown models that differ from the students’ incorrect models, but are believable, so students’ models change. These results are encouraging, as animations are relatively easy to incorporate into a lesson, provided adequate animations are available.

Students at all grade levels struggle to learn chemistry, and many are never successful (Nakhleh, 1992). To add to the difficulty, chemistry involves using
descriptions at a level we cannot see with the naked eye to explain things we can see. However, it is important for people to understand that matter is composed of tiny particles that we cannot see with the naked eye and that these particles are responsible for the observations we can make of macroscopic natural phenomena. The National Research Council asserts “to understand the physical and chemical basis of a system, one must ultimately consider the structure of matter at the atomic and subatomic scales to discover how it influences the system’s larger scale structures, properties, and functions” (NRC, 2012, p. 103).

Chemistry is not an easy subject for teachers to convey to their students either. Teaching is a demonstration of the teacher’s content knowledge; they cannot teach content they do not understand (Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013; Anderson & Mitchner, 1994). A few studies address either preservice teachers’ content knowledge or building inservice teachers’ content knowledge through professional development. Haidar (1997) found many prospective chemistry teachers’ content knowledge of basic chemistry concepts varied from exhibiting specific misconceptions to no understanding at all. The one topic which teachers in Haidar’s study understood was balancing chemical equations. Haidar also found a fragmented understanding of concepts rather than a solid understanding. Valanides (2000) studied primary student teachers’ understanding of the particulate nature of matter and found that most struggled with relating the particulate level explanations to the macroscopic observations. The preservice teachers also had difficulty in differentiating between physical and chemical changes. He suggested that conceptual change-based instructional materials and interventions are needed for both preservice and inservice teachers to address this
deficiency in content knowledge. Similarly, Tatar (2011) found that preservice primary teachers had misconceptions related to the states of matter. They had difficulty connecting the macroscopic and particulate views. Tatar noted this misunderstanding may be related to how particles in different states of matter are illustrated in textbooks. Teachers need to also be aware of their students’ misconceptions. Sadler et al. (2013) suggest an awareness of student misconceptions is a component of pedagogical content knowledge that may “allow teachers to construct experiences, demonstrations, experiments, or discussions that make students commit to and then test their own ideas” (p. 1043).

Given the debate about when students should be introduced to the particulate nature of matter (AAAS, 2009; NRC, 1996; NGSS Lead States, 2013; Gabel et al., 1987), additional research needs to be done on how and when to teach the particulate nature of matter. It is often not emphasized, but instead is a topic that we tend to assume students pick up during their study of chemistry. As a fundamental concept of chemistry, it is a topic we should be teaching directly. When considering when and how to teach chemistry topics, we need to be aware of the misconceptions students bring to the classroom. These misconceptions are often resistant to change, and often persist into adulthood (Nakhleh, 1992).

**Spatial Ability in Chemistry**

Spatial ability has been linked to success in STEM fields (Wai, Lubinski, & Benbow, 2009), including chemistry (e.g., Pribyl & Bodner, 1987; Wu & Shah, 2003; Stieff, 2013). Some topics in chemistry, like the shapes of molecules, are obviously spatial in nature, while others, such as stoichiometry, are less so.
Regardless, research has shown that a variety of topics in chemistry are correlated with spatial ability (e.g., Pribyl & Bodner, 1987; Wu & Shah, 2004; Stieff, 2013). Much of the research connecting spatial ability to achievement in chemistry has been at the college level, with few studies including pre-college students (Wu & Shah, 2004). In addition, several studies have investigated sex differences in spatial ability in general (e.g., see Voyer, Voyer, & Bryden, 1995 for a review) as well as in chemistry (Stieff, 2013). Wai, Lubinski, and Benbow (2009) also connected spatial ability in adolescence with student achievement and pursuit of STEM degrees and careers as adults. Several studies have also shown that spatial abilities can be learned and improved through training (e.g. Uttal et al., 2013).

While it is difficult to find a general definition of spatial ability, Hegarty (2010) says that spatial thinking, “involves thinking about the shapes and arrangements of objects in space and about spatial processes, such as the deformation of objects, and the movement of objects of other entities through space” (p. 266). Cohen and Hegarty (2007) zone in on spatial visualization in particular, differentiating between internal mental representations (i.e. ability to mentally store and manipulate visual-spatial representations or situations in the mind) and external representations (i.e. visual-spatial displays that include both static and dynamic images). One of the difficulties in consulting the literature on spatial ability in chemistry is that there are a variety of terms for different types of spatial ability in the literature. Linn and Petersen (1985) used three categories in their meta-analysis of spatial ability studies: spatial perception, mental rotation, and spatial visualization. Spatial perception involves determining spatial relationships in relation to the orientation of the observer; this means the person is visualizing objects
from different perspectives. Mental rotation is the ability to mentally manipulate objects in two- or three-dimensions. Spatial visualization is the most complex of the three spatial abilities, and involves multi-step mental manipulations of objects. Wu and Shah (2004) also used three spatial abilities to categorize the studies in their meta-analysis of the visuo-spatial chemistry literature. They used the terms spatial visualization (complex sequence of mental manipulations of an object), closure flexibility (speed at which a person can identify a spatial pattern), and spatial relations (mental transformations that are simpler than those required by spatial visualization). In both cases, the term spatial visualization was used, but different definitions were provided in each. Linn and Petersen (1985) referred to complex mental manipulations of objects, and listed simple mental rotations as a separate category while Wu and Shah (2004) combined the two under the broad umbrella of spatial visualization.

In this dissertation, the terms used by the authors in their papers are reported as they used them. In terms of searching the literature, spatial visualization in chemistry was broadly interpreted as including mental manipulations (simple or complex) of objects in two- or three-dimensions. This is also the definition of spatial visualization I used throughout the dissertation. I also use Hegarty and Waller’s (2005) descriptions of internal spatial visualization ability and external spatial visualization ability. They differentiate the two by noting that internal visualizations include the ability to mentally manipulate and view representations while external visualizations are spatial displays that occur outside of the mind, such as models or drawings. I view mental rotation as a subset of spatial visualization in that it requires the mental manipulation of either an internal (e.g. mental model) or external (e.g. a drawing, physical model, actual object)
Nersessian (2008) defined models as “representations of objects, processes, or events that capture structural, behavioral, or functional relations significant to understanding” (p. 392). In discussing mental models in science, she built on the work of Johnson-Laird (1983) and Craik (1943) to suggest that mental modeling includes an iconic representation (i.e. the model) but also tacit and explicit knowledge of the domain of science in order to create a mental model. Nersessian (2008) noted that people not only use mental models for mundane situations, such as her example of whether a couch would fit through a doorway and into a room, but also in complex situations such as those found in science. She defined a mental model as “a conceptual system representing the physical system that is being reasoned about” noting it is an abstraction of the real situation (p. 409). Nersessian (2008) also noted using simulative mental modeling as in thought experiments may contribute to empirical insights.

Wu and Shah (2004) conducted a literature review of visuospatial ability in chemistry. They point out the number of correlational studies linking spatial ability and chemistry at the college level, but the lack of similar information at the pre-college level. They note the existence of a few studies that include high school students as participants, but call for additional work to be done linking the early years of learning chemistry and spatial ability. Wu and Shah (2004) specifically mention that a substantial amount of chemistry instruction is done at the high school level; this is clearly the level to which they were referring as pre-college chemistry. However, the Next Generation Science Standards include foundational ideas in chemistry beginning in 5th grade, so studies are needed with middle school students as well.
Gender Differences in Spatial Ability

Males generally outperform females on assessments of spatial ability (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). Research has shown that the difference is more pronounced for certain types of spatial ability (e.g. mental rotation, spatial perception) than for spatial visualization (Voyer, Voyer, & Bryden, 1995). However, the authors pointed out a lack of consensus in the literature as to what spatial abilities really are or how to categorize them; this lead to some difficulty in categorizing what assessments were measuring. Carter, LaRussa, and Bodner (1987) suggested that gender differences in spatial ability may explain the differences in achievement in general chemistry courses. The scores for males on tests of visuospatial ability also tend to be more varied than the scores of females, though it is not known why (Halpern, Benbow, Geary, Gur, Hyde, and Gernsbacher, 2007). This variability means the gender difference in visuospatial ability is more pronounced at either end of the spectrum.

Barke, (1993) conducted a study of middle school students in Germany, testing the correlation between spatial ability and intelligence. He also considered training spatial skills, particularly with respect to gender differences. He found no correlation between spatial ability and IQ for seventh graders. Barke (1993) did, however find a correlation for both eighth grade and ninth grade students; the correlation was present overall and for both girls and boys. He suggests these results indicate that teachers should avoid the use of problems that require the application of spatial ability in seventh grade, but these types of problems would be appropriate starting in eighth grade. He also suggests that real spatial models should be used before drawn models. Barke (1993) also states that spatial abilities of both boys and girls can be improved using concrete models and appropriate
Spatial Ability: Spanning the Levels of Representation

Hegarty (2010) identified two components of spatial intelligence: flexible strategy choice and meta-representational competence. Flexible strategy choice involves deciding when to use mental imagery versus analytical thinking. Meta-representational competence refers to the awareness of which is the best representation to use for addressing a specific task and the ability to use the properly chosen representation effectively (diSessa, 2004). This metacognition may be especially important when we consider its relation to Johnstone’s (1991; 1993) triangle. Johnstone noted that novice chemistry students often get stuck at one vertex or along one side of the triangle. They have a difficult time moving to the fluid center of the triangle where the expert resides. One of the issues lies in understanding and using the many representations and symbols in chemistry; sometimes there are many representations for a single problem. Hegarty’s (2010) notion of meta-representational competence may be what separates the novice chemist from the expert. The experts likely are aware of and able to choose the most appropriate representations for the task and use them effectively to address the problem. diSessa (2004) asserts “to the extent that we want to and believe we can help students do the things scientists do, [meta-representational competence], … should be a part of our goals” (p. 296). Teaching students this component of spatial intelligence could help them navigate Johnstone’s triangle.

Problem Solving

Bodner and McMillen (1986) suggest chemistry courses are the ideal place to teach students problem solving skills. They also point out that historically, the way
students have been taught to solve problems is by watching their instructor work through examples. In studying first semester general chemistry students, they found a significant correlation between spatial ability and chemistry test scores. The correlation was significant between spatial ability and obviously spatial questions, but it was also significant between spatial ability and other questions. They attribute this second correlation to the first of Polya’s (1945) four stages to solving a problem: understanding the problem. Bodner and McMillen (1986) suggest this stage is most related to spatial ability because it requires students to take apart the problem and identify the most salient parts; students need to make sense of the problem before they can make a plan to solve the problem, carry out the plan, or look back at their work (Polya, 1945).

Other researchers have also shown significant correlations exist between spatial ability and questions that require problem-solving skills (Grabow, 2003; Bodner & Guay, 1997; Carter, LaRussa, & Bodner, 1987). Bodner & McMillen (1986) use Hayes’ (1980) definition of a problem, which says that you have a problem if there is a gap between where you are and where you want to be and you don’t have an idea how to bridge the gap. They explain that using this definition, they can differentiate between the words problem and exercise. If you read a question and know what to do right away, it’s an exercise. If you don’t immediately know how to address the question, you have a problem. Novice problem solvers use spatial visualization skills to address a problem until an algorithm or analytical rule for the situation is known (Schwartz & Black, 1996; Stieff, 2007). Heyworth (1999) similarly found that high school chemistry students who were experts at solving problems on concentration simply worked through the math to get to the solution. In contract, the novice problem solvers had to start at the goal of the
problem and work backwards to identify the intermediate steps before they could work through the math. Carter et al. (1987) found the correlation with spatial ability was stronger for questions that tested problem solving skills rather than rote memorization or the use of an algorithm. To the instructor, most chemistry questions assigned to students are really exercises; they are practice in using an algorithm or analytical application of memorized facts. However, to the chemistry student, many of the assigned questions truly are problems. Even if the instructor provides the algorithm, the novice students need to use their spatial skills to make sense of the problem before the algorithm can be applied.

**Visuospatial or Analytic Approach to Problem Solving?**

Hegarty (2010) conducted a study where students completed two tests of spatial visualization: the Paper Folding Test (Eckstrom, French, Harman, & Derman, 1976) and the Vandenberg Mental Rotations Tests (Vandenberg & Kuse, 1978). One group of students thought aloud while answering the questions. Another group of students were given a list of strategies to rank based on which ones they used the most in solving the problems. The list of strategies was based on the think aloud responses of the first group of students. Hegarty (2010) found that most people used mental imagery to solve the tasks on the assessments, but many also used analytic strategies (i.e. algorithms, heuristics). Using at least one analytic strategy was correlated with test performance on the Paper Folding Test but not the Vandenberg Mental Rotations Tests (Hegarty, 2010). Other researchers examining the use of visual versus analytical strategies to solve similar problems found that novices rely on visual strategies first until analytical rules are learned and experts use visual strategies when in novel situations (Schwartz & Black,
1996; Stieff, 2007). Once the analytical rule is known, it often becomes the default method for routine problem solving. This points to the importance of developing visuospatial thinking; it is the default problem solving strategy before the appropriate analytical strategy is known. Hegarty (2010) points out that training in visualization should be supplemented by training in complementary analytical thinking. Stieff, Dixon, Ryu, Kumi, and Hegarty (2014) found that targeted training in both mental imagery and analytic problem solving strategies eliminated sex differences in achievement in a college chemistry course. They also found that a male advantage remained when training only occurred for a single type of strategy. In a study on undergraduate organic chemistry students, Stieff (2013) also found that students who used analytic strategies increased their success in identifying stereochemical isomers (i.e. whether two molecules are identical or mirror images), but also significantly increased the time required to complete each task.

**Improving Students’ Spatial Ability**

Researchers have argued that spatial visualizations are most effective when introduced at an early age precisely because of the concrete thought of the young students (Shibley, Milakofsky, Bender, & Patterson, 2003; Abdullah & Shariff, 2008). This assertion is in opposition of the views of Piaget, who would argue that the concrete operational stage of young students is an impediment to completing spatial tasks. This research says that when students are still in the concrete operational stage, they benefit from the concrete representations of the microscopic particles and processes (Shibley et al., 2003; Abdullah & Shariff, 2008).

Alias, Black, and Gray (2002) showed that targeted instruction in discipline-
specific spatial reasoning was more effective for helping students learn to reason about spatial phenomena in engineering than instruction on spatial reasoning in general. Students’ difficulty in understanding the particulate nature of matter may be due to poor spatial visualization ability (Gabel, Samuel, & Hunn, 1987). Thus, it is possible that targeted instruction in chemistry-specific spatial tasks will improve students’ ability to spatially reason in chemistry contexts. Uttal, Meadow, Tipton, Hand, Alden, Warren, & Newcombe (2013) meta-analyzed 217 research studies investigating training in spatial skills and concluded that “spatially enriched education could pay substantial dividends in increasing participation in mathematics, science, and engineering” (p. 352). The results of this study are encouraging given the demand for STEM majors. However, teachers need to be sure that students experience “spatially enriched” education in their classrooms (Uttal et al., 2013).

Yezierski and Birk (2006) conducted a study with eighth graders, tenth graders, and college general chemistry students to explore whether using particulate level animations in the classroom would help close overcome students’ misconceptions of the particulate nature of matter. They attribute the significant gains of the control group partially to students’ spatial visualization ability, though no spatial visualization assessments were administered. Yezierski and Birk (2006) also report that the female students performed significantly better than the male students. A drawback of this study was that the data for all groups of students was reported together, making it impossible to tell whether the significant gains in the experimental groups differed by grade level. The authors suggest that particulate level animations should be used in classroom to benefit all students, but also that they could help close the gender gap in chemistry achievement.
Tuckey, Selvaratnam, and Bradley (1991) conducted a study of undergraduate students’ difficulties with three-dimensional studies. They created a two-hour long intervention in which students were instructed on and practiced several kinds of spatial reasoning commonly used in chemistry. The instruction included an illustration of the areas on the pretest in which students had difficulty, explanation of the specific ways the two-dimensional illustrations represented three-dimensional structures (for instance, a description of the wedge and dash system), and practice with reflections and rotations. After instruction, the students’ performance on a spatial chemistry assessment was significantly improved. In addition, no significant difference was found between the males and females in the study, indicating the training worked equally well for both genders.

Urhahne, Nick, and Schanze (2008) conducted a study of high school and college students who learned about the reactions of carbon using either three-dimensional simulations or two-dimensional illustrations. A significant correlation between spatial ability and the acquisition of conceptual knowledge on the carbon assessment was observed for all groups. They found that for the university students, it made no difference whether the students learned with the two- or three-dimensional illustrations. However, the secondary students in the study who received instruction using the three-dimensional simulations performed significantly better than those who used the two-dimensional illustrations. The authors concluded the difference was because the younger students lacked experience working with visual representations in chemistry, so the training in the three-dimensional format helped them more. They also suggest that the reason the college students’ conceptual knowledge wasn’t significantly linked to the simulations was that
they may have already known more about the carbon concepts being assessed, making
the learning environment irrelevant.

Small and Morton (1983) studied the use of training workbooks to improve the
spatial visualization skills of college organic chemistry students. The workbook exercises
included “drawing and interpreting two-dimensional models, building and manipulating
three-dimensional models, and imagining the manipulation of three-dimensional models”
(p. 42). The authors report after the spatial training, the experimental group had
significantly higher total scores on the final examination overall and for the spatial
questions. While Small and Morton did not administer spatial assessments after the
intervention, the students who received training in spatial skills improved their chemistry
performance.

Ben-Chaim, Lappan, and Houang (1988) studied the effects of a unit designed to
intentionally teach spatial skills to 5th to 8th grade students. During the unit, students
physically manipulated objects, building and drawing objects made of cubes. Prior to the
unit, they found a difference in spatial ability by grade and gender. As students got older,
their spatial ability increased. In general, the boys performed significantly better on pre-
tests of spatial ability than the girls, though there was variation in the sample resulting in
a large overlap in performance between the subgroups. The post-tests showed that both
boys and girls benefited from the instruction, making similar sized gains. Also, the gains
in spatial ability persisted as illustrated by additional spatial ability testing 4 weeks and 1
year later. While this study was conducted in mathematics classrooms, the spatial skills
learned are the same types of spatial skills needed for chemistry. It is plausible, then, that
a similar intervention could be used to improve the spatial abilities of chemistry students.
Limitations

The biggest limitation or perhaps caution to this set of studies is that we cannot infer causal relationships from correlations. While the data show that mental rotation ability and understanding the particulate nature of matter are significantly, positively correlated for both middle school students and middle school teachers, we cannot draw any conclusions from the correlation alone about why they are related or whether one causes the other. Also, while the correlations appear to be growing in strength from pre-sixth grade instruction to post-seventh grade instruction, this data was collected at the same time with two different groups of students. This cross-sectional data collection does not allow for comparisons to be made over the two-year time span as a longitudinal study design would allow. Instead, we are only able to judge whether student performance on the assessments improved pre to post instruction within the same grade.

The teachers in this study were selected from a group of teachers who had voluntarily signed up for ongoing professional development on project-based instruction. They knew they would also be experiencing two example project-based units throughout the professional development, including one focused on middle school chemistry content. This convenience sample of teachers may not be representative of the larger population of middle school teachers. However, the teachers represent nine different middle schools across five different districts. At the time of data collection, the teachers ranged in teaching experience from being a first year teacher to 29 years of classroom experience. A limitation of this convenience sample of teachers means that caution should be used in interpreting and generalizing the data and instead the transferability of the outcomes to other situations should be considered.
Another limitation is the fact that the content of the daily instruction during the chemistry units is a bit of a mystery. The seventh-grade teachers were provided a unit to use, but the ways in which each teacher adapted and implemented the unit within their own classroom is unknown. The sixth-grade teachers used units of their own design for teaching chemistry, and these are somewhat unknown as well. While the teachers of both grade levels provided some outline of their unit, there may also be a gap between what the teachers said they were doing in their classrooms and what really happened. The lack of information about what the teachers actually taught in their classrooms impacts the interpretation of the data in that it limits the comparisons we can make between pre and post-test data. While we could judge whether there was an improvement in performance on the assessments, we are unable to attribute those changes to specific classroom practices. The lack of information on the units also makes it difficult to be sure that all of the concepts on the content assessment were covered in class. For instance, on the Particulate Nature of Matter Assessment (Yezierski, 2003), some of the questions have vocabulary terms with which students may or may not be familiar.

**Research Questions and Methodology**

This set of studies uses a mixed-methods design overall. Each of the manuscripts draws their data from parts of or a combination of the instruments and/or interviews as described. Seventh grade students were asked to complete assessments prior to and after receiving instruction in chemistry in the classroom. The assessments were given on computers within their regular science classrooms. Selected students were also interviewed; the interviews occurred during the school day, in the students’ schools. In addition, middle school science teachers took assessments prior to and after participating
in targeted, content-specific professional development. The teachers completed the assessments via computer in the professional development meeting rooms. Selected teachers were interviewed as well. In the first paper (Chapter 2) and the third paper (Chapter 4), correlations and item analysis are used to show how spatial ability and understanding of chemistry are related. Mental rotation was chosen as the specific spatial ability under consideration. This author considers mental rotation to be a subset of spatial visualization, falling under the internal representations described by Cohen and Hegarty (2005). Mental rotation was chosen for two main reasons. First, it is the most common spatial thinking ability measured within the existing studies on the relationship between spatial ability and understanding chemistry content. Second, an instrument exists that many agree measures mental rotation specifically and not another spatial skill either alone or mixed with mental rotation.

The papers in the following chapters provide a view of middle school chemistry, focusing on learning and teaching about the particulate nature of matter and its relationship to spatial reasoning ability. While sub-questions are presented with each manuscript (See Table 1.1 for a list of research questions and hypotheses by chapter), overall, this set of manuscripts seeks to address the research question, In what ways are spatial reasoning and understanding of chemistry content related in middle school classrooms?
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<td>2</td>
<td>In what ways are spatial reasoning ability and understanding of the particulate nature of matter related for middle school students?</td>
<td>A significant, positive correlation would exist between spatial reasoning (mental rotation) and understanding of the particulate nature of matter.</td>
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<td></td>
<td>How does the spatial ability of students choosing correct responses compare to those exhibiting alternative conceptions about the particulate nature of matter?</td>
<td>The spatial score for students choosing the correct response would be significantly higher than the spatial score for students who chose other responses.</td>
</tr>
<tr>
<td>3</td>
<td>In what ways do students’ pre-understandings of middle school chemistry concepts differ by spatial ability?</td>
<td>Students with higher spatial abilities will have less-fragmented understandings of chemistry than students with lower spatial ability.</td>
</tr>
<tr>
<td></td>
<td>How are spatial reasoning ability and understanding of the particulate nature of matter related for middle school teachers?</td>
<td>A significant, positive correlation between spatial reasoning ability and understanding of the particulate nature of matter for teachers.</td>
</tr>
<tr>
<td>4</td>
<td>What chemistry related misconceptions do middle school science and mathematics teachers hold?</td>
<td>A significant difference in spatial ability among answer choices would exist on the Particulate Nature of Matter Assessment.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>At least some teachers would exhibit a fragmented understanding of chemistry concepts.</td>
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Chapter 2

Middle School Students’ Chemistry Content Knowledge and Spatial Ability

Abstract

This quantitative study examines the relationship between middle level students’ spatial reasoning ability and their understanding of the particulate nature of matter. The United States Next Generation Science Standards bring the particulate nature of matter to the forefront in the 6-8 grade band, where the emphasis is placed on understanding matter and its interactions at the particulate level. Research with college students has shown a correlation between understanding of chemistry content and spatial reasoning ability. This is the first study to explore the relationship between spatial reasoning and students’ understanding of chemistry concepts at the middle school level. A significant positive correlation was observed between middle level students’ spatial reasoning and their understanding of the particulate nature of matter. Item analysis also showed that the mean spatial scores of students choosing differed by answer choice. Though we are unable to infer cause and effect relationship from correlational data, these results illustrate a need to investigate this relationship further as well as identify the relationship between different spatial abilities (not just mental rotation) and other chemistry concepts. These results also highlight the need for spatially rich experiences in middle school classrooms to potentially improve the spatial reasoning ability of students in addition to developing a strong foundation in the principles of chemistry.
Introduction

Early natural philosophers did not have the technology to understand the structure and function of matter. Instead, they offered their best ideas based on their observations. Democritus was the first to suggest that matter is made up of tiny, indivisible particles that determined the properties of a substance (Brock, 1992). Later, Aristotle put forth the idea that matter was composed of four elements – earth, air, fire, and water. Democritus’ view of matter required more imagination and abstract thought; there were no tools available in ancient Greece to allow the early natural philosophers to see atoms or to be able to experimentally confirm their ideas. Aristotle’s view of matter could be sensed by humans; they could feel whether something was hot, cold, wet, or dry, making Democritus’ atomism seem to be pure imagination (Brock, 1992). Students likely feel the same disbelief the first time their teacher suggests matter is made of tiny particles they cannot see. Students can make observations at the macroscopic level of the properties of matter. They can see things like color, shape, and size or observe changes to each through physical or chemical processes. They can see that an ice cube melts into a puddle of liquid when left in a warm room. They can also observe the opposite process occur if the liquid is poured into an ice cube tray and placed in the freezer. When students are asked to explain why these changes or properties occur, they run into problems. Rather than dealing with something they can interact with directly, they are being asked to think abstractly about matter and trust the science their teacher is telling them.

In this study, we explored the relationship between students’ understanding of middle school chemistry concepts and spatial reasoning. One of the challenges in teaching chemistry is scale. While students are able to observe matter at a macroscopic
level, the chemistry is happening at the particulate level they cannot see. Thinking abstractly about atoms, molecules, and ions requires the development of mental models and spatial reasoning in order to visualize and mentally manipulate the particles interacting to explain the observed phenomena. This study is the first, to our knowledge, to examine the relationship between spatial reasoning ability and middle school students’ understanding of chemistry.

**Background**

Research has shown that when asking middle school students to explain scientific phenomena their understanding should be expected to be an “explanatory framework” as opposed to a fully developed theory (Samarapungavan & Wiers, 1997). Students at this age have a piecewise understanding of science. They are aware there is a sub-atomic level as well as the more easily observed macroscopic level, but it is hard for them to move between those two levels; middle school students are still making the transition from considering only the macroscopic to including the particulate view as well (Nakhleh, Samarapungavan, & Saglam, 2005). Studies have shown a correlation between spatial ability and achievement in general chemistry and organic chemistry on both spatial and non-spatial tasks (Pribyl & Bodner, 1987; Bodner & McMillen, 1986). Spatial ability is often cited as a contributing factor in students’ success in chemistry (Bodner & Guay, 1997; Gabel & Hunn, 1987). However, many of these studies are focused at the college level. Studies show the correlations between spatial ability and chemistry content understanding exist not only for problems that are obviously spatial in nature, such as rotating molecules to identify isomers, but also questions that require problem solving...
skills, such as stoichiometry (Bodner & Guay, 1997; Grabow, 2003; Carter, LaRussa, & Bodner, 1987).

The particulate nature of matter refers to the atomic, molecular, and ionic interactions that result in chemical phenomena (Bunce & Gabel, 2002). The particulate nature of matter is a concept that states: 1) matter is composed of tiny, individual particles, 2) the particles are always in motion, and 3) the nature of the particles and their interactions define the properties of matter. When discussing the importance of the particulate nature of matter, Margel, Eylon, & Scherz (2008) said that understanding the concept of the particulate nature of matter illuminates “relationships between structure, properties, and applications of materials, which will in turn help us understand phenomena in the world around us.” The power of chemistry to explain natural phenomena lies at the atomic level (Hesse & Anderson, 1992; Treagust & Chittleborough, 2001), but students are often expected to make the link between the macroscopic observations and the sub-microscopic explanations on their own. Researchers have suggested that instruction is needed at the atomic level in order for students to develop an understanding of chemistry (Ahtee & Varjola, 1998). One reason students struggle to view matter as particulate is that they continue to base their ideas solely on their observations rather than incorporating new abstract information about the particles in matter from their science lessons in school into their framework of understanding about matter (Lee et al., 1993; Nakhleh, Samarakungavan, & Saglam, 2005).

Middle school is an important time for considering the role of spatial reasoning in understanding content. Preteens, the age of students in our study, undergo a second wave
of brain development in the area of spatial reasoning, which puts them at an ideal age for improving spatial reasoning (Giedd et al., 1999). Middle school NGSS also mark a shift in thinking from the easily observed macroscopic phenomena to the consideration of particles in matter. These particles require the use of abstract thought and mental models in order to visualize and reason through the explanations for phenomena. Appendix E in the United States Next Generation Science Standards (NGSS; NGSS Lead States, 2013) describes the progressions of the disciplinary core ideas (DCI) across grade bands. The Structure of Matter (PS1.A) progression starts at the K-2 grade band with the idea that matter has properties and that objects can be made from smaller pieces. The idea that matter is made up of tiny particles too small to see (the particulate nature of matter) is addressed at the 5th grade level along with the idea that properties can be used to identify materials. In the 6-8 grade band, the particulate nature of matter is brought to the forefront: “the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter” (NGSS Lead States, 2013). Within the physical science standards, students are asked to model the changes in particle motion when thermal energy is added or removed (MS-PS1-4), determine whether a chemical reaction has occurred (MS-PS1-2), model the conservation of mass at the atomic level (MS-PS1-5), and to investigate the relationships among energy transferred, matter, mass, and energy of particles (MS-PS3-4). Students are able to apply their emerging understanding of the particulate nature of matter in the life sciences and Earth and space sciences standards. The high school grade band continues this focus and uses it to explain the
chemistry that we see. In particular, there is an emphasis on the electrons within an atom, since that is where most chemical interactions happen.

One of the difficulties in consulting the literature on spatial ability in chemistry is that there are a variety of terms for different types of spatial ability in the literature. Linn and Petersen (1985) used three categories in their meta-analysis of spatial ability studies: spatial perception, mental rotation, and spatial visualization. Spatial perception involves determining spatial relationships in relation to the orientation of the observer; this means the person is visualizing objects from different perspectives. Mental rotation is the ability to mentally manipulate objects in two- or three-dimensions. Spatial visualization is the most complex of the three spatial abilities, and involves multi-step mental manipulations of objects. Wu and Shah (2004) also used three spatial abilities to categorize the studies in their meta-analysis of the visuo-spatial chemistry literature. They used the terms spatial visualization (complex sequence of mental manipulations of an object), closure flexibility (speed at which a person can identify a spatial pattern), and spatial relations (mental transformations that are simpler than those required by spatial visualization). In both cases, the term spatial visualization was used, but different definitions were provided in each. Linn and Petersen (1985) referred to complex mental manipulations of objects, and listed simple mental rotations as a separate category while Wu and Shah (2004) combined the two under the broad umbrella of spatial visualization. Wu and Shah (2004) conducted a literature review of visuospatial ability in chemistry. They point out the number of correlational studies linking spatial ability and chemistry at the college level, but the lack of similar information at the pre-college level. They note the existence of a few studies that include high school students as participants, but call for additional
work to be done linking the early years of learning chemistry and spatial ability. Wu and Shah (2004) specifically mention that a substantial amount of chemistry instruction is done at the high school level; this is clearly the level to which they were referring as pre-college chemistry. However, the NGSS include foundational ideas in chemistry beginning in 5th grade, thus studies are also needed with 5th-8th grade students.

Methods

This study uses a quantitative design to address the research questions 1) In what ways are spatial reasoning ability and understanding of the particulate nature of matter related for middle school students? and 2) How does the spatial ability of students choosing correct responses about the particulate nature of matter compare to the spatial ability of students choosing incorrect responses? For the first question, the authors hypothesized a significant, positive correlation would exist between spatial reasoning (mental rotation) and understanding of the particulate nature of matter. For the second question, the authors hypothesized that the spatial score for students choosing the correct response would be significantly higher than the spatial score for students who chose other responses.

Data include students’ scores on the Purdue Spatial Visualization Test of Rotations (PSVT: Bodner & Guay, 1997) and the Particulate Nature of Matter Assessment (ParNoMA; Yezierski, 2003) to assess spatial reasoning and understanding of matter, respectively. While a variety of spatial assessments are available for use, the PSVT was chosen for two main reasons. First, it was the assessment most often used by other studies examining the relationship between spatial reasoning and understanding of chemistry; in order to bring this connection to the middle school level, the authors wanted
to use the same assessment. Second, there is a lack of consensus on definitions and assessments of types of spatial reasoning in the literature; some terms, such as spatial visualization, are defined in different ways. Mental rotation is among the best defined spatial reasoning ability and there is also consensus that the PSVT does indeed measure mental rotation. In the authors’ view, mental rotation ability is a subset of spatial visualization in that it requires the mental manipulation of either an internal (e.g. mental model) or external (e.g. a drawing, physical model, actual object) representation.

This data set included 98 sixth grade students and 179 seventh grade students from two middle schools in the south east central United States. Sixth grade students were drawn from two teachers’ classrooms. Seventh grade students were drawn from three teachers’ classrooms. Eighth grade students were not included in the data set because chemistry is not taught to 8th grade students in the middle schools in which the data were collected. Students completed the PSVT and the ParNoMA prior to and after experiencing a chemistry unit in their classrooms. The PSVT is designed to test the students’ ability to mentally/visually rotate three-dimensional objects. While the PSVT was originally designed for use with college students, prior studies have shown acceptable reliability data when used with middle school students (Wilhelm et al., 2013). The ParNoMA was designed for use with middle school students to measure their understanding of matter at the particulate (i.e. atoms, molecules, etc.) level. Acceptable reliability data were previously reported when used in middle school classrooms (Yezierski, 2003; Bridle & Yezierski, 2011). Correlations were calculated for sixth and seventh grade students prior to and after experiencing a chemistry unit in their
classrooms. Spearman’s Rho was calculated for each time point in the data set as the data were not normally distributed.

To address the second research question, item analysis was also conducted on ParNoMA questions. Kruskal-Wallis tests were used to compare the PSVT scores by ParNoMA question answer choice. Descriptive statistics were also used to show the average spatial ability by response choice for each question.

**Results**

Spearman’s correlation was run to determine the relationship between students’ spatial reasoning scores (PSVT) and chemistry content knowledge scores (ParNoMA) prior to and after the students experienced a chemistry unit in either 6th or 7th grade (see Table 2.1 for mean scores at each time point and Table 2.2 for correlation data); the correlations were significant at all time points. A moderate, positive correlation was found between PSVT and ParNoMA scores prior to the chemistry unit in 6th grade (r(96) = .364, p < .01), after the chemistry unit in 6th grade (r(96) = .452, p < .01), prior to the chemistry unit in 7th grade (r(179) = .403, p < .01), and after the chemistry unit in 7th grade (r(145) = .492, p < .01). Cronbach’s Alpha was calculated as .77, .76, .79, and .74 for the PSVT pre and post 6th grade and pre and post 7th grade respectively. Cronbach’s Alpha was also calculated as .51, .51, .70 and .78 for the ParNoMA pre and post 6th grade and pre and post 7th grade respectively.
Table 2.1

Percent Correct on Particulate Nature of Matter Assessment (ParNoMA) and Purdue Spatial Visualization Test of Rotations (PSVT)

<table>
<thead>
<tr>
<th></th>
<th>ParNoMA</th>
<th></th>
<th>PSVT</th>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>6th</td>
<td>36.5%</td>
<td>45.5%</td>
<td>29.4%</td>
</tr>
<tr>
<td>7th</td>
<td>42.2%</td>
<td>48.4%</td>
<td>41.7%</td>
</tr>
</tbody>
</table>

N=98 for 6th grade tests, N=181 for 7th grade pre-tests and N=147 for 7th grade post-tests

Table 2.2

Correlations Between ParNoMA and PSVT Scores

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th></th>
<th>Post</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rs</td>
<td>Strength</td>
<td>rs</td>
<td>Strength</td>
</tr>
<tr>
<td>6th</td>
<td>.364</td>
<td>Moderate</td>
<td>.452</td>
<td>Moderate</td>
</tr>
<tr>
<td>7th</td>
<td>.403</td>
<td>Moderate</td>
<td>.492</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

All correlations are significant at the p < .01 level. N=98 for 6th grade tests, N=181 for 7th grade pre-tests and N=147 for 7th grade post-tests

Item analysis was also conducted on items on the ParNoMA to assess whether the spatial scores of students choosing the correct answer differed significantly from the spatial score of students choosing other responses. The item analysis was conducted for the 7th grade post-unit time point, as the assessment includes vocabulary words that would require some instruction to differentiate among. By the time students have experienced chemistry instruction in their classroom for the second time, they have likely been exposed to all of the vocabulary on the assessment whereas students at other time points may not. The average spatial reasoning score (i.e. PSVT score) tended to be higher for students choosing the correct response than for students choosing the incorrect responses. For instance, a question asked students to identify which process would make water molecules larger. The correct response, none of the above (E), was chosen by 38
students out of the 147 students taking the tests after their chemistry unit in 7th grade. The mean spatial score for students choosing E was 50.53%. Most of the other students chose A freezing (N = 63, M = 39.29%), while others chose B melting (N = 19, M = 36.32%), C evaporation (N = 12, M = 37.92), or D condensation (N = 15, M = 35.33%). A Kruskal-Wallis test showed the spatial score for students choosing the correct response differed significantly from the spatial scores for students choosing other responses ($\chi^2(4)$ = 11.593, $p = .021$). Mann-Whitney U tests showed the mean spatial score for students choosing answer E (M = 50.53%) was significantly higher than for students who chose the most common misconception, a. freezing (M = 39.29%, U = 793.500, $p = .004$) as well as compared to students choosing all other answers combined (M = 38.07%, U = 1329.000, $p = .001$). Students also struggled in answering a question about which part of the system (i.e. types and locations of bonds) requires energy during evaporation or vaporization. Thirty students chose the correct answer, D break the water molecules away from other water molecules (M = 48.67%). Other students chose A break the bonds between the hydrogen atoms (N = 41, M = 42.07%), B form new bonds between the atoms (N = 17, M = 26.76%), C break the bonds between the oxygen and hydrogen atoms in the molecules (N = 44, M = 38.86%), or E form new bonds between the molecules (N = 15, M = 48.00%). A Kruskal-Wallis test showed the spatial score for students choosing answer D (M = 48.67%) was significantly different from students choosing other responses ($\chi^2(4)$ = 15.249, $p = .002$). Mann-Whitney U tests showed the spatial score for students choosing answer D (M = 48.67%) was significantly higher than for students who chose the most common misconception, C (M = 38.86%, U = 442.500, $p = .016$) as well as compared to students choosing all other answers. Though many students (N=41) also
chose A, there was no significant difference between the spatial scores (M = 42.07%) compared to those students who chose the correct answer, D (M = 48.67%).

### Table 2.3

**N, Spatial Scores, and Kruskal-Wallis Test Results for 7th Grade Post-Test Item Analysis**

<table>
<thead>
<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N</strong></td>
<td>A</td>
<td>2</td>
<td>23</td>
<td>63</td>
<td>71</td>
<td>41</td>
<td>25</td>
<td>47</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>26</td>
<td>109</td>
<td>19</td>
<td>23</td>
<td>17</td>
<td>61</td>
<td>6</td>
<td>44</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>95</td>
<td>9</td>
<td>12</td>
<td>37</td>
<td>44</td>
<td>10</td>
<td>36</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>18</td>
<td>5</td>
<td>15</td>
<td>6</td>
<td>30</td>
<td>8</td>
<td>29</td>
<td>39</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>6</td>
<td>1</td>
<td>38</td>
<td>10</td>
<td>43</td>
<td>8</td>
<td>8</td>
<td>61</td>
<td>3</td>
</tr>
</tbody>
</table>

|       | A   | 27.50 | 35.00 | 40.00 | 45.00 | 45.00 | 32.50 | 40.00 | 30.00 | 27.50 | 45.00 |
|       | B   | 37.50 | 45.00 | 35.00 | 20.00 | 20.00 | 40.00 | 70.00 | 35.00 | 40.00 | 42.50 |
|       | C   | 45.00 | 20.00 | 25.00 | 40.00 | 40.00 | 40.00 | 45.00 | 40.00 | 30.00 | 32.50 |
|       | D   | 35.00 | 28.00 | 40.00 | 37.50 | 50.00 | 25.00 | 35.00 | 45.00 | 27.50 | 20.00 |
|       | E   | 22.50 | 40.00 | 55.00 | 50.00 | 40.00 | 50.00 | 37.50 | 50.00 | 50.00 | 37.50 |

|       |       |       |       |       |       |       |       |       |       |       |
|       |       |       |       |       |       |       |       |       |       |       |
| **p** | .016  | .003  | .021  | .000  | .020  | .072  | .252  | .034  | .027  | .001  |
|       |       |       |       |       |       |       |       |       |       |       |
| **χ²**| 12.26 | 15.92 | 11.59 | 20.12 | 15.2  | 8.6   | 10.38 | 10.98 | 17.93 | 17.93 |
|       |       |       |       |       |       |       |       |       |       |       |
| **df**| 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |

Table Note: shaded cells denote correct response choice

While a significant difference among spatial scores for students choosing each of the responses was found for seventeen of the questions, no significant difference was
observed on three of the questions (See table 3 for the spatial scores, N, and significance for each question). On thirteen of the seventeen questions where a significant difference was observed, the mean spatial score was highest for those students choosing the correct response.

**Discussion**

*In what ways are spatial reasoning ability and understanding of the particulate nature of matter related for middle school students?* A strong foundation in the fundamental ideas of chemistry, such as the particulate nature of matter, is essential for students to learn chemistry (Gabel, Samuel, & Hunn, 1987). Prior studies have shown significant correlations between measures of spatial reasoning, such as the PVST that measures mental rotation, and exam scores in college chemistry courses (Stieff, 2013). The college-level studies hold true both for items that are obviously spatial in nature (e.g. stereoisomers, molecular geometries) and those that are not (e.g. problem solving, stoichiometry). This study shows a statistically significant moderate correlation between mental rotation and students’ understanding of the particulate nature of matter, which is the primary focus of the NGSS middle school chemistry standards. While we cannot draw causation from the correlation of data, these results point towards the need to investigate the inclusion of spatially rich experiences in middle school classrooms in order to improve the spatial reasoning ability of students. For instance, Lee et al. (1993) found that using a targeted curriculum designed to address both the macroscopic and particulate scales helped compared to a curriculum that focused on scientific facts, though not all students were able to grasp the particulate nature of matter in the end. Also, studies should be done to investigate why mental rotation in particular is correlated
with the understanding of the particulate nature of matter. When considering matter at the particulate nature of matter, where does mental rotation fit? To consider matter at the particulate level, one must first visualize the particles within matter. Then, to understand the interactions or changes of state of matter, one must also be able to mentally manipulate these visualizations, at times rotating them. In this study, the Particulate Nature of Matter Assessment (Yezierski, 2003) was used which uses water as the context for many of the questions. For instance, in one question, students are shown an image of the water molecules in ice. Then, they are asked to decide which other image shows what the water molecules would look like when the water changed to a liquid state. Students need to mentally manipulate the water molecules in each image and combine these models with their understanding of chemistry in order to decide which image is the correct choice. Even in other questions, students are picturing water molecules in this way in order to understand the spatial relationships inherent within each problem. While the relationship between spatial reasoning and understanding chemistry can be inferred, studies should be conducted that better probe the relationship and understand why mental rotation is relevant. Also, studies should be conducted that examine other types of spatial reasoning that may play a role in understanding the particulate nature of matter.

*How does the spatial ability of students choosing correct responses compare to those exhibiting common alternative conceptions about the particulate nature of matter?*

The item analysis in this study adds another component to the link between spatial reasoning ability and understanding chemistry. The data showed a significant difference among the spatial scores for students who chose different responses. Students who chose the correct response had, in general, higher mental rotation scores than students who
chose incorrect responses. For instance when students considered processes that would change the size of molecules, those who chose the correct answer saying that no change of state would make water molecules increase in size had a higher average spatial ability than the nearly twice as many students who said that freezing would make water molecules bigger. Lee et al. (1993) found students would describe molecules in substances undergoing changes of state as “expanding, contracting, melting, evaporating, and so forth” rather than explaining how the molecules within the matter moved. The students in their study didn’t seem to separate the properties of the molecules themselves from the properties of a bulk substance. While they addressed the misconception through the use of a targeted curriculum that considered both the macroscopic and particulate features of matter, not all students were able to understand matter at the particulate level in the end. Given the correlation between spatial ability and understanding of matter at the particulate level, perhaps improving students’ spatial ability would help students like those in Lee et al.’s (1993) study who struggle with understanding matter at the particulate level. On another example question, students who chose the correct answer (energy is used for breaking intermolecular bonds) had significantly better spatial skills than those who focused on intermolecular forces. Considering the correlation between spatial reasoning and understanding the particulate nature of matter, we can surmise that students who were better able to create and manipulate particulate level mental models of water changing from a liquid to a gas were better able to identify that the energy was used in separating the molecules from each other rather than the common misconception that the molecules themselves break apart into atoms. In this question, the manipulation of the molecules in the mental model illustrate the need for the spatial skill of mental
rotation specifically. As Bodner and Guay (1997) suggest, it is not impossible to be successful in chemistry with poor spatial skills. However, their work and others’ that show correlations between spatial ability and performance in chemistry should encourage students to improve their spatial skills so they may have an easier time dealing with the many spatial tasks inherent in the field of chemistry. In addition, teachers should be made aware of this link and provide opportunities for their students to develop their spatial ability.

**Conclusions and Significance**

It is important for students to form a sound understanding of the particulate nature of matter in middle school because an understanding of this and similar fundamental concepts in chemistry are needed in order to succeed in other science courses. A common science sequence in high school is Biology in 9th grade, Chemistry in 10th grade, Physics in 11th grade, and an elective or advanced science course in 12th grade. Biology includes many concepts that require an understanding of matter and its interactions at the particulate level. Some of the topics that frequently appear in a biology textbook include “osmosis and diffusion, photosynthesis, cellular respiration, digestion, transpiration, the water cycle, and ecological matter cycling” (Lee et al., 1993). Since biology is often taught prior to chemistry in high schools, it is imperative that students gain an understanding of matter and its interactions at the particulate level while in middle school.

A limitation of this study is the inclusion of two different groups of students for the different grade levels. Following the growth in spatial reasoning ability and also chemistry content knowledge over time for the same group of students would allow for
the comparison of the data between grades as well as pre-unit to post-unit. It would also be helpful to know why students chose particular answers. Was the choice of an incorrect answer due to a misconception or perhaps a vocabulary issue? That being said, this study illustrates the need for continued research in the area of spatial reasoning with chemistry instruction at the middle school level. This study also shows the correlation between spatial reasoning and understanding of chemistry content that others have found at the college level also exists at the middle school level.

Another limitation of the study is inherent to using correlation. While we would like to say that the students’ spatial ability impacted their ability to learn and understand the particulate nature of matter, all we can say is that the two are directly related. We are unable to say whether one causes the other or infer anything about why they are related from the significant correlation alone. Other information is needed to better understand why the two things are significantly correlated.

The results also illustrate a need to identify the relationship between different spatial abilities (not just mental rotation) and chemistry concepts beyond the particulate nature of matter in middle schools. Spatial ability has been linked to success in other STEM fields as well as chemistry (Wai, Lubienski, & Benbow, 2009); other types of spatial ability besides the mental rotation addressed in this study have also been linked to success in STEM. In this study, as the students learned more about chemistry, their scores on the ParNoMA increased as well as the correlation between the ParNoMA and PSVT. This study illustrates the need for spatially rich curricula to be developed that will potentially improve students’ spatial reasoning ability in addition to chemistry concepts.
Chapter 3

Middle School Students’ Understanding of Chemistry Prior to Formal Instruction

Abstract

One challenge in teaching chemistry is the issue of scale. Elementary school science is focused on the macroscopic observations of phenomena, while middle school students are asked to consider these same phenomena at the particulate level, which is where the chemistry happens. Many middle school students find difficulty in moving between the two levels, though students with better spatial reasoning ability may better be able to visualize the particulate nature of matter. Since a correlation exists between understanding chemistry content and a student’s spatial reasoning ability, we interviewed eight sixth-grade students of varying spatial reasoning ability to determine their chemistry understandings prior to formal classroom instruction. Teachers should use caution in accepting keywords as correct responses without probing for reasoning; students of differing spatial ability showed different levels of understanding of chemical phenomena. While lower spatial students tended to use keywords without explanation, higher spatial students used more consistent reasoning. Without a firm understanding of fundamental chemistry concepts, like the particulate nature of matter, students have difficulty with other chemistry topics. Teachers can aid in understanding the particulate nature of matter by asking questions that include the role of particles in chemical and physical phenomena in addition to macroscopic views.
We worked to identify students’ pre-understanding of middle school chemistry concepts before being introduced to Chemistry lessons for the first time. One of the challenges in teaching chemistry is the scale. While students are able to observe chemistry at a macroscopic level, the chemistry is happening at the particulate level they cannot see; they need to think abstractly about the tiny atoms, molecules, and ions. This requires the development of mental models and spatial reasoning in order to visualize and mentally manipulate the particles interacting to explain the observed phenomena. We examined students’ reasoning for chemistry phenomena to see if students with higher spatial ability had a better understanding of Chemistry than students with lower spatial ability.

Research has shown that when asking middle school students to explain scientific phenomena their understanding should be expected to be an “explanatory framework” as opposed to a fully developed theory (Samarapungavan & Wiers, 1997, p.587). Students at this age have a piecewise understanding of science. They are aware there is a sub-atomic level and also of the more easily observed macroscopic level, but it is hard for them to move between those two levels; middle school students are still making the transition from considering only the macroscopic views to including the particulate view as well. (Nahkleh et al., 2005). Studies have shown a correlation between spatial ability and achievement in general chemistry and organic chemistry on both spatial and non-spatial tasks (Pribyl & Bodner, 1987; Bodner & McMillen, 1986). A related study (Cole & Wilhelm, under review) has shown that middle school students’ spatial reasoning ability is correlated to their understanding of the particulate nature of matter, similar to the studies with college students.
Middle school is an important time for considering the role of spatial reasoning in understanding content. Preteens, the age of students in our study, undergo a second wave of brain development which puts them at an ideal age for improving spatial reasoning (Giedd et al., 1999). Middle school NGSS also mark a shift in thinking from the easily observed macroscopic phenomena to the consideration of particles in matter. These particles require the use of abstract thought and mental models in order to visualize and reason through the explanations for phenomena.

We wanted to identify how pre-understandings middle school students have before experiencing chemistry lessons for the first time may vary by the students’ spatial ability. Since spatial ability and classroom performance are linked, knowing how pre-understandings may differ by spatial ability adds information for teachers to use when identifying misconceptions and differentiating lessons in the classroom.

**Particulate Nature of Matter in the NGSS**

Appendix E in the Next Generation Science Standards (NGSS: NGSS Lead States, 2013) describes the progressions of the disciplinary core ideas (DCI) across grade bands. The Structure of Matter (PS1.A) progression starts at the K-2 grade band with the idea that matter has properties and that objects can be made from smaller pieces. The idea that matter is made up of tiny particles too small to see (the particulate nature of matter) is addressed at the 5th grade level along with the idea that properties can be used to identify materials. In the 6-8 grade band, the particulate nature of matter is brought to the forefront (see Table 3.1 for a list of middle school standards related to the particulate nature of matter): “the fact that matter is composed of atoms and molecules can be used
to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter” (NGSS Lead States, 2013, Appendix E p. 41).

Table 3.1.
Next Generation Science Standards for the Particulate Nature of Matter

<table>
<thead>
<tr>
<th>NGSS Performance Expectations in Physical Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-PS1-1</td>
</tr>
<tr>
<td>6-PS1-4</td>
</tr>
<tr>
<td>7-PS1-2</td>
</tr>
<tr>
<td>7-PS1-5</td>
</tr>
<tr>
<td>7-PS3-4</td>
</tr>
<tr>
<td>7-LS1-6</td>
</tr>
<tr>
<td>7-LS1-7</td>
</tr>
</tbody>
</table>

NGSS Lead States, 2013

Within the physical science standards, students are asked to model the changes in particle motion when thermal energy is added or removed (MS-PS1-4), determine whether a chemical reaction has occurred (MS-PS1-2), model the conservation of mass at the atomic level (MS-PS1-5), and to investigate the relationships among energy transferred, matter, mass, and energy of particles (MS-PS3-4). Students are able to apply their emerging understanding of the particulate nature of matter in the life sciences and Earth
and space sciences standards. The high school grade band continues this focus and uses it to explain the chemistry that we see. In particular, there is an emphasis on the electrons within an atom, since that is where much of the chemistry lies.

**Clinical Interviews: Formative Assessment of Students’ Understanding**

We conducted interviews with middle school students in the southeast central United States. Interviews were chosen to explore the ways in which students of differing spatial abilities described chemical phenomena. We used the Purdue Spatial Visualization Test of Rotations to assess the spatial reasoning ability of students (PSVT; Bodner & Guay, 1997). This test is designed to test the students’ ability to mentally/visually rotate three-dimensional objects. While the PSVT was originally designed for use with college students, prior studies have shown acceptable reliability data when used with middle school students (e.g. Wilhelm et al., 2013). We interviewed eight middle school students, two boys and two girls from each of two classrooms. We intentionally chose one boy and one girl from each classroom who performed well on this spatial assessment (labeled high-spatial throughout), and one boy and one girl who scored low on the spatial assessment (labeled low-spatial throughout).

The interviews were broken down into two sections. The first section included vocabulary questions about chemistry and matter where students were asked about a term and then asked for an example and non-example of each with justification. The second part of the interview was a set of demonstrations that were examples of chemical and/or physical changes. The students were asked if they thought the item would have a change in weight and then asked to explain their reasoning using either verbal or drawn responses.
Student Responses and Reasoning

In the vocabulary section of our interview we asked students to give definitions of chemistry-related terms. In order to gauge the accuracy of their responses, we looked for accepted definitions of the terms for comparison. One term we struggled to define was chemical. In common use, a chemical is often thought of as an unnatural substance, a dangerous substance, and/or something found in a laboratory. The American Chemical Society uses the word chemical in many of the same ways they use matter, saying that everything is made of chemicals (www.acs.org). The Merriam-Webster dictionary defines chemical as something “of, relating to, used in, or produced by chemistry or the phenomena of chemistry” (Merriam-Webster, 2015). Without a clear, common definition for chemical, it is no wonder why many students are unclear about the meaning.

When asked to define chemicals Collin, a low-spatial boy, said that chemicals are “Substances used to do stuff in chemistry.” As an example of a chemical he said “um… maybe like gasoline or something” and a non-example would be “water … cause you can drink it I guess, I kind of think of a chemical as something you don’t want to drink?”

Natalie, a high-spatial girl, said that chemicals are “the things that make up certain stuff like there are different chemicals in like water or juice or stuff I guess.” Her example of a chemical was “oxygen may be one, maybe? … because um I can’t really see it and it’s a gas and maybe because like chemicals are like really small and they like make up stuff? … chemicals are in oxygen and makes us, it helps us breathe and stuff.” While neither student was clear on the definition of chemical, Natalie seemed to understand that chemicals were not only bad or dangerous, but could be beneficial as well. She also noted
that chemicals “make up stuff” as opposed to Collin who only named things as chemicals that he did not want to drink.

When we asked students to define matter, many of the students mentioned the phases of matter - solids, liquids, and gases. Our accepted definition for this term was “any substance that has mass or takes up space” (American Chemical Society, 2016). Amber, a low-spatial girl, said that matter is “something you can touch I think, or feel.” Her example of matter clarified that by saying “Um like a ball or something that like solid, like it could be solid, it could be liquid, it could be gas”, however when asked for a non-example, she responded with “Uh like water or gas,” contradicting her statement that matter could be a liquid or gas in her example. Cody (high-spatial) told us matter is “anything that is a solid, liquid or gas.” He gave gold as an example of matter explaining it was a solid and said light was not matter because, “it’s not a solid liquid or gas, it’s an energy.” While both used the phases of matter – solid, liquid, or gas – as part of their reasoning for what matter was, Cody understood that energy was not matter, while Amber’s response showed a conflict with her initial definition.

For the demonstration section of the interview students had similar ideas despite their spatial ability. Both Bill and Collin (high-spatial and low-spatial respectively) correctly believed that the ice cube would weigh the same after melting because nothing was taken away or added. When showed the candle burning, they both applied the same framework of thought, focusing on the melting wax, and incorrectly said the candle would weigh the same after burning. Neither was able to explain that matter was being lost as a gas from the combustion reaction of the flame. Both Bill and Collin identified
the physical change (melting) but failed to note the chemical change (combustion) in the candle.

**Summary**

While the conservation of mass appears in the middle grades in the NGSS, the particulate nature of matter is first described in fifth grade. We might expect students entering sixth grade to have some intuitive understandings about the conservation of mass, but not necessarily a firm understanding. However, we should expect them to know something about the particulate nature of matter. Our students tended to rely on the macroscopic descriptions rather than the particulate explanations for the phenomena in question. Students were able to identify parts of chemistry and give definitions but some used unclear or inconsistent reasoning. The students’ thinking was revealed in their reasoning more than in the definitions; they may provide a definition, but the descriptions revealed whether the students understood the definition or concept.

**What pre-understandings do middle school students hold about chemistry concepts?**

These students showed that they knew that chemistry, chemicals, and matter were a part of science, but they were not able to give accurate definitions or examples. Throughout the vocabulary portion of the interview, the students used keywords such as “chemistry” or “molecules” or “elements” in their reasoning while answering questions. However, these keywords they were not always used correctly; in some cases, it appeared that the students were using all the related terms they knew, hoping one would be deemed correct. When asked about chemicals, three of four low-spatial students used water as a non-example of a chemical. Two of those students reasoned water was not a chemical because you can drink it. This implies that those two students think of a chemical as
something that is harmful to your body. Two high-spatial students (Cody and Natalie), provided examples of chemicals with reasonable definitions where as two other high-spatial students (Bill and Jenny) were unable to provide any examples of chemicals. During the demonstrations, the students could have used the Law of Conservation of Mass in their reasoning for why they said the item would weigh the same or different after the change it underwent. We saw the students were generally able to use the concept correctly, though most were unable to define or provide an example of the Law of Conservation of Mass earlier. Perhaps part of the reason these students couldn’t define the term chemical is because it does not have a clear, common definition. Matter and chemistry do have clear definitions, but the lower spatial ability students still struggled with those. These students used the terminology that they knew or were familiar with in their justification but it was unclear whether they really understood the terms they were using.

**How do these chemistry understandings vary by spatial ability?**

There were differences in the responses that high-spatial students gave versus the responses that low-spatial students gave. Whenever students with high spatial ability gave a response they would provide some sort of logical explanation for their reasoning such as when Cody explained that matter is “anything that is a solid, liquid, or gas” with an example of gold because it is a solid and light was an example of something that is not matter because it is an energy. Whereas Amber (low-spatial) said that matter is something that you can touch and feel with an example being a ball because it is a solid and a non-example being water. These responses relate to the explanatory frameworks mentioned by Samarapungavan and Wiers (1997); the students are able to provide pieces of
explanations, but were not able to give a fully developed theory, such as the definition of matter and what classifies something as matter. The responses given by the high-spatial students had more consistent reasoning than the low-spatial students.

**Relevance for Classroom Teachers**

Students have exposure to physical science in elementary grades and have also gathered information from their life experiences. Teachers need to be cautious when identifying pre-understanding and ask for explanation or reasoning as well as definitions. Middle school teachers should be aware of differences in understanding among students of differing spatial abilities; they may think about or describe chemical phenomena differently. While the concepts may seem complex or more advanced, the NGSS middle school standards ask students to consider fundamental ideas in chemistry. These concepts are taught in high school and college chemistry courses, but they are often taught as a set of facts rather than being considered in depth to develop a conceptual understanding. Yet, students struggle with understanding later chemistry concepts when they fail to grasp the fundamental concepts in chemistry (Gabel et al., 1987). Students are being exposed to chemistry formally for the first time in middle school. Middle school science teachers have the opportunity and responsibility to help students develop a firm understanding of two fundamental concepts in chemistry – the particulate nature of matter and the Law of Conservation of Mass – before they are expected to apply them. The students we interviewed were often able to give a definition or an example, but were not usually able to explain why, indicating the students were using a fragmented framework of understanding of matter at this point. Similar to other studies (e.g. Lee et al., 1993; Nakhleh et al., 2005), this study shows that students are struggling to make the transition
from thinking about matter at the macroscopic level to also considering matter at the particulate level and perhaps more importantly, connecting the two levels. Researchers have used the term *babbling* to mean students making sometimes incoherent or inexpert attempts at explaining their thinking and *gurgling* to describe learners using all the technical terms they can in hopes of one being correct to earn points or acknowledgement from the teacher (Malara & Navarra, 2003; Scataglini-Belghitar & Mason 2011). Many of the responses our students gave fit one of these categories. The high-spatial students were not always clear, sometimes *babbling* to get their understanding across, but they used more consistent reasoning and provided more explanations. The low-spatial students tended to provide definitions by using any terms they knew were related to chemistry; they often *gurgled* the related terms hoping one of them would be correct, often with little to no explanation.

Teachers should be cautious about accepting keywords as correct responses without probing into the students’ understanding. Some students may be able to provide key words without understanding how they fit a concept. On the other hand, students who are unable to provide specific keywords may be able to provide more information showing they have an initial understanding of a concept. Without a firm understanding of fundamental chemistry concepts, many students struggle to learn and apply later chemistry topics (Gabel et al., 1987). One way to aid students in learning about the particulate nature of matter is to use lesson like the example shown (see Appendix C) where students are asked to consider what the particles in a simple baking soda and vinegar reaction are doing while learning about the Law of Conservation of Mass. Throughout the lesson, students are asked to describe what they are seeing (i.e. the
macroscopic view) as well as describing and drawing what the particles they cannot see are doing within the reaction. Teachers can also probe for understanding by asking students to relate the two – how do the particles help explain the phenomenon under observation? Regardless of the activity used, when probing for information about how the particulate level can explain the macroscopic level, teachers need to be cautious to listen to the entire explanation and not just focus on keywords.
Chapter 4

Connecting Middle School Teachers’ Mental Rotation Ability and Chemistry Understandings

Abstract

Middle school teachers are asked to teach all areas of science, though they may hold alternative conceptions in one or more science content areas. Since teachers cannot effectively teach what they themselves do not understand, identifying alternative conceptions held by middle school science teachers is important. Prior research has shown a correlation between understanding of chemistry content and spatial reasoning ability (e.g., Pribyl & Bodner, 1987; Wu & Shah, 2003; Stieff, 2013), raising the importance of developing the spatial reasoning ability of both teachers and students. Few studies examine in-service middle school teachers’ understanding of chemistry concepts or spatial reasoning ability. Middle school teachers’ chemistry understanding and spatial reasoning ability were assessed through interviews and written assessments prior to participating in chemistry professional development. A significant, positive correlation between spatial reasoning ability and chemistry understanding was found ($r (18) = .482$, $p = .031$). Teachers were able to provide definitions, but at times struggled with examples or applications of definitions at the particulate level. Teachers who used consistent reasoning when defining and providing examples for terms tended to have higher spatial reasoning ability than teachers who used inconsistent reasoning. Many of the teachers in this study have been teaching for several years, possibly instilling some of their alternative conceptions with their students.
Introduction

The Next Generation Science Standards ask teachers to teach multiple areas of science (i.e. chemistry, biology, Earth/Space science, physics) within a single grade level, where previously they may have only been tasked with one or two areas of science (NGSS Lead States, 2013). However, licensing requirements for middle school science teachers vary by state; few states require that middle school teachers have a strong content background that covers all areas of science. Instead, some middle school science teachers can be licensed based on a degree in a single science content area. Even when preservice teachers do take courses in a variety of science domains they are often left with a shallow, superficial coverage of science content. When middle school science teachers are licensed without requiring a deep, wide coverage of the areas of science they will be expected to teach, they are likely to enter the classroom unprepared or underprepared in at least one area of science. Regardless of pedagogical knowledge or skill, teachers are simply unable to teach science they do not understand themselves. Middle school teachers are also asked to teach chemistry at an important transition point for their students. They are asked to help students move from understanding matter at the macroscopic level to understanding matter at the not easily observed particulate level (Nakleh, 1992). Researchers have shown there is a correlation between students’ understanding of chemistry content and their spatial reasoning ability at a variety of grade levels (Bodner & Guay, 1997; Stieff, 2013, Chapter 2). We contend that this relationship between spatial reasoning and understanding of chemistry extends to teachers as well. This mixed-methods study seeks to address the research questions 1) How are spatial reasoning ability and understanding of the particulate nature of matter related for middle school teachers? 2) What chemistry related misconceptions do middle school teachers hold?
Background

Many students at all grade levels struggle with learning chemistry (Nakhleh, 1992). One reason many people struggle with understanding chemistry is that they fail to understand fundamental concepts and are unable to build an understanding of more advanced concepts (Gabel, Samuel, & Hunn, 1987). Understanding of the particulate nature of matter, a fundamental concept in chemistry, relies on understanding this concept on multiple levels. Johnstone (1991, 1993) noted that chemistry requires an ability to move freely among the sub-microscopic (i.e. atomic/subatomic), macroscopic (i.e. what we can easily see with the naked eye), and representational (i.e. models or drawings of chemical phenomena, symbols, equations) levels used to describe matter and its interactions. Chemistry professionals are able to slide from area to area in this triangle, often working in the fuzzy middle region where levels are blended together while novices are often stuck on one edge or in one corner of the triangle. Each of the levels represented in the triangle are needed to explain phenomena and should not be portrayed separately; the ability to shift among and blend the three areas is needed to truly understand chemistry (Russell et al., 1997; Treagust, Chittleborough, & Mamiala, 2003). Most chemistry instruction is focused at the symbolic level, relying on symbols, models, and mathematics in chemistry classrooms (Gabel, 1999; Johnstone, 1991; Nakhleh, 1993).

Wright (2003) asserts, “when students learn about atoms they are given the key to unlocking many of the doors across the sciences, in physics, chemistry, biology, and earth science” (p. 18). Talanquer (2008) analyzed the research literature on alternative conceptions students hold about the particulate nature of matter, noting a major transition occurring when students start thinking about matter as composed of particles that have definite attributes.
Spatial ability is often cited as a contributing factor in students’ success in chemistry; understanding of chemistry content and spatial reasoning ability are positively correlated (Bodner & Guay, 1997; Gabel, Samuel, & Hunn, 1987; Bodner & McMillen, 1986; Grabow, 2003). Wu and Shah (2004) conducted a meta-analysis of “visuospatial thinking” in chemistry, concluding that more research is needed at the pre-college level. They note the existence of a few studies that include high school students as participants, but call for additional work to be done linking the early years of learning chemistry and spatial ability. Like many other researchers, Wu and Shah appear to be referring only to the high school level when discussing the pre-college level. However, fundamental chemistry concepts appear in the NGSS beginning in fifth grade with the first mention that “matter is made of particles too small to be seen” (NGSS Lead States, 2013). The middle school standards continue adding fundamental concepts such as the conservation of mass, thermochemistry, and signs of chemical reactions. Additionally, the middle school standards are an important transitional point, where chemistry is addressed from a particulate view rather than the macroscopic view on which the elementary standards are based (Talanquer, 2008). Clearly, examining the role spatial reasoning plays in understanding middle school chemistry concepts should be included in researchers’ views of the pre-college level.

In many science classrooms, teaching is a demonstration of the teacher’s science content knowledge (Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013; Anderson & Mitchner, 1994). Studies that focus on science teachers’ understanding of subject matter are rare, though some studies address either preservice teachers’ content knowledge or building inservice teachers’ content knowledge through professional development. Haidar (1997) found prospective chemistry teachers’ content knowledge of basic chemistry concepts varied,
with many teachers’ knowledge ranging from exhibiting specific misconceptions to no understanding. The only topic on which teachers in Haidar’s study showed good understanding was balancing chemical equations. Haidar also found that the prospective teachers in his study had a fragmented understanding of the concepts rather than a continuous understanding. Valanides (2000) studied primary student teachers’ understanding of the particulate nature of matter and found that most had difficulties relating the particulate level explanations to the macroscopic observations. The preservice teachers also struggled to differentiate between physical and chemical changes. He suggested that conceptual change-based instructional materials and interventions are needed for both preservice and inservice teachers to address this deficiency in content knowledge. Similarly, Tatar (2011) found that preservice primary teachers had misconceptions related to the states of matter. These preservice teachers had trouble connecting the macroscopic observations of matter to which they were accustomed to the arrangement and motion of the particles within each state of matter.

Tatar noted that the way the particles are drawn in each state of matter in textbook examples may play a role in these misunderstandings. Khourey-Bowers and Simonis (2004) reported on a study in which middle school science teachers were provided with professional development to enhance self-efficacy, chemistry content knowledge, and pedagogical content knowledge. While no content knowledge outcomes were reported, the researchers suggested that improving teachers’ science teaching self-efficacy was an important piece in working towards science literacy for all students. Teachers also need to be aware of their students’ misconceptions. Sadler et al. (2013) suggest an awareness of student misconceptions is a component of pedagogical content knowledge that may “allow teachers to construct
experiences, demonstrations, experiments, or discussions that make students commit to and then test their own ideas” (p. 1043).

While we cannot infer cause and effect relationships from correlational data, research has shown a correlation between spatial ability and understanding chemistry content (e.g., Pribyl & Bodner, 1987; Wu & Shah, 2003; Stieff, 2013). It stands to reason that if this relationship exists among students of chemistry, then it may also exist for teachers of chemistry. Teachers with poor spatial ability may be struggling with the same ideas in chemistry as some of their students. Thus, they may be struggling with being able to explain concepts at the particulate level as needed for full understanding. Do they understand the particulate level? Are they stuck in one corner of the triangle themselves? Is their knowledge of or facility with the triangle or spatial reasoning limiting what their students can learn in their classroom? Middle school students have been shown to have a fragmented understanding of science, often struggling to make the transition between the particulate explanations and macroscopic observations of matter (Nakhleh, Samarapungavan, & Saglam, 2005; Samarapungavan & Wiers, 1997). It is important to also investigate what kind of understanding of matter middle school science teachers possess.

Methods

This study uses a concurrent mixed-methods design to investigate the research questions 1) How are spatial reasoning ability and understanding of the particulate nature of matter related for middle school teachers? and 2) What chemistry related misconceptions do middle school science and mathematics teachers hold? Quantitative data includes teachers’ scores on the Particulate Nature of Matter Assessment (ParNoMA; Yezierski, 2003) and the Purdue Spatial Visualization Test of Rotations (PSVT; Bodner & Guay, 1997). Qualitative
data is drawn from a written survey and a semi-structured interview. Twenty-two middle school mathematics and science teachers are included in the sample; all teachers who identified themselves are mathematics teachers currently are also certified to teach middle grades science. Only one of the teachers in this sample was not teaching science at the time of data collection. The teachers are drawn from 9 schools spanning 5 school districts in a state in the southeast central United States. Teaching experience ranged from one to twenty-nine years of experience. Teacher participants were selected based on their interest in attending a year-long series of professional development workshops led by the authors that included middle school chemistry as the focus science content. Six seventh grade teachers were also asked to participate in semi-structured interviews prior to professional development.

To address the first research question, correlations were calculated between teachers’ scores on the ParNoMA and the PSVT. In addition, item analysis was used to investigate whether PSVT scores were different for teachers choosing the correct answer compared to other responses. The authors began this analysis with the hypothesis that the spatial score for teachers choosing the correct response would be higher than teachers who chose an answer that indicated a common alternative conception.

To address the second research question, data were drawn from the ParNoMA responses, the written survey, and the interviews. Six seventh grade teachers participated in semi-structured interviews that included questions about chemistry vocabulary, demonstrations related to the conservation of mass, questions on spatial relationships of provided figures, and questions related to their background in learning and teaching chemistry. The first survey asked teachers to respond to the same questions as the first portion of the interview. These questions asked teachers to provide definitions of chemistry terms, followed
by examples and non-examples of the term as well as reasoning for the examples.

**Results**

Teachers’ scores on the Particulate Nature of Matter Assessment (ParNoMA) ranged from 55% to 100%, with a mean score of 89%. Scores on the Purdue Spatial Visualization Test of Rotations (PSVT) ranged from 5% to 90% correct, with a mean of 52%. A moderate, positive correlation was observed between the teachers’ PSVT and ParNoMA scores, which was statistically significant \( r (18) = .482, p = .031 \). Cronbach’s Alpha was calculated for the ParNoMA and PSVT as .72 and .76 respectively.

Item analysis showed a significant difference between spatial scores for teachers who chose the correct response compared to teachers who chose an alternative response on only one question; the Kruskal-Wallis test showed the spatial score for teachers choosing the correct response differed significantly from the spatial scores for teachers choosing another response \( \chi^2 (4) = 6.095, p = .014 \). The question where a significant difference was found asked how the size of a water molecule in the gas phase compared to the size of a molecule in the solid phase.

The average spatial score for the 16 teachers who chose the correct response, E. the same weight as, was 57.5%. The average spatial score for the 4 teachers who chose B. lighter than was 30.0%. No teachers chose the other response choices of A. smaller than, C. heavier than, or D. larger than. No significant differences among spatial scores for teachers choosing different responses were observed for any other questions. For most questions, teachers chose either the correct response or a single, alternative response.

Teachers were asked to provide a definition for matter, an example for matter and how they knew that was an example of matter, and then a non-example of matter and how they knew that was not an example of matter. Similarly, they were asked to define the term
chemicals, then provide examples and non-examples of chemicals and an explanation of the examples they gave. Teachers were specifically told to share what they thought the term (chemicals or matter) meant if they were not sure of the correct definition; the authors did not specify to the teachers what was meant by the correct or real definition. Table 4.1 shows the terms teachers focused on in their definitions for matter and chemicals.

**Table 4.1**

*Terms Used by Teachers to Define Matter and Chemicals*

<table>
<thead>
<tr>
<th>Matter</th>
<th>Chemicals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (77%)</td>
<td>Atoms/Molecules/Ions (61%)</td>
</tr>
<tr>
<td>Takes up space (82%)</td>
<td>Compounds/Mixtures/Combinations (32%)</td>
</tr>
<tr>
<td>Volume (9%)</td>
<td>Elements (27%)</td>
</tr>
<tr>
<td>Everything (14%)</td>
<td>Everything (18%)</td>
</tr>
<tr>
<td></td>
<td>Matter (14%)</td>
</tr>
<tr>
<td></td>
<td>Interactions (14%)</td>
</tr>
<tr>
<td></td>
<td>Manmade (5%)</td>
</tr>
</tbody>
</table>

Note: percentage denotes the percentage of teachers using the term

A common, accepted definition of matter is anything that “has mass and takes up space” (ACS, 2016). Some other definitions go further, adding matter is composed “predominantly of atoms consisting of protons, neutrons, and electrons, that constitutes the observable universe, and that is interconvertible with energy” (Merriam-Webster, 2016).

When defining matter, most teachers (77%) mentioned mass or that it had to take up space (82%). A few of the teachers (9%) mentioned volume instead of taking up space. Fourteen percent of the teachers said matter is everything. The majority of the teachers (77%) were able to use consistent reasoning and provide examples and non-examples that were consistent with their definition. Nine percent used inconsistent reasoning, while the same portion (9%) provided unclear or vague responses, and a smaller portion (5%) of the teachers provided no reasons for their examples and non-examples (see Figure 4.1).
Figure 4.1: Percentage of Teachers Answering Consistently for Matter.

One of the teachers who used consistent reasoning said that matter is “anything that has mass and takes up space.” This teacher then went on to say that air is matter because “it has mass and takes up space” and that heat energy was not matter because “it does not have mass or take up space.” Another teacher who used consistent reasoning also said “anything that has mass and takes up space” is matter. She went on to say that a book is an example of matter because “it has mass and takes up space” and that feelings were not matter because they “don’t physically take up space or have mass.” These two teachers consistently used the common definition to not only say what matter was but also to explain why things were or were not examples of matter, focusing on whether or not the examples had mass and took up space. A teacher who used inconsistent reasoning when defining matter said “What isn’t matter? Matter is everything.” She then went on to add that “It’s matter because matter makes up the universe” without saying what exactly the example was. She also said “Light is not matter. It’s energy.” While her non-example was accurate to the accepted definition of matter, it did not fit with her earlier definition that said that everything was matter. Another teacher
who used inconsistent reasoning said matter is “composed of atoms.” She provided water as an example of matter, reasoning “it takes up space and has mass” and said “a black hole? It doesn’t have mass” for a non-example. This teacher provided the accepted definition of matter for a reason that water was matter, though she did not use has mass or takes up space as part of her definition. She also provided a hesitant response of a black hole (the question mark is hers) for a non-example of matter and suggested a lack of mass for the reason a black hole is not matter, which neither matches her definition of matter nor is it scientifically accurate.

When it comes to chemical, a common, accepted definition was more difficult to identify. The American Chemical Society (2016) says everything is made of chemicals. Dictionaries often use chemical as part of the definition, such as when Merriam-Webster (2016), which defines chemical as “of, relating to, used in, or produced by chemistry or the phenomena of chemistry.” The Royal Society of Chemistry (Haxton, 2016) conducted a survey of what people thought about the definition and safety of chemicals, concluding (among other things) that chemists need to be careful about how scientific definitions are used and that chemists should provide a good definition of the term chemical. They suggest a variety of things that may go into that definition, without providing a concrete definition themselves. The closest the study’s author gets to suggesting a definition is saying that a chemical is “a substance with constant composition and defined properties.” Unlike the definitions provided for matter, the teachers in the current study gave more varied definitions of the term chemical. Most of the teachers (61%) mentioned atoms or molecules in their definition. About a third (32%) mentioned compounds, mixtures, or some sort of combination. A similar number of teachers (27%) mentioned elements specifically. Other teachers said that everything was a chemical (18%), chemicals were matter (14%), chemicals required
interactions (14%), or that chemicals were manmade (5%). While most teachers were able to provide consistent definitions and examples for matter, the responses for chemicals were less successful. About a third of the teachers (36%) used consistent reasoning in their definitions and examples, while another third (32%) used inconsistent reasoning, and the final third either provided no reasons for their examples (14%) or provided responses that were vague or unclear (18%; See Figure 4.2).

One of the teachers said that chemicals were composed of atoms. She then went on to provide an example and non-example that were consistent with that definition. She said that water is a chemical because “it’s composed of atoms – two hydrogen atoms and one oxygen.” For the non-example, she said “light is not a chemical because it is not composed of atoms, though it can be emitted by atoms.” Another teacher defined chemicals as “any substance containing atoms.” She provided water as an example, saying “it is made of atoms

![Consistency of Reasoning for Chemicals](image)

*Figure 4.2: Percentage of Teachers Answering Consistently for Chemicals*

of elements.” Her non-example was love, reasoning that “love is a feeling triggered by chemicals in the brain.” Both of these teachers focused on the presence of atoms in chemicals, explaining they knew their examples were chemicals because they contained atoms and their
non-examples were not chemicals because they didn’t contain atoms, though they could be produced by atoms or chemicals. In contrast, one of the teachers said “chemicals are matter that is made from the periodic table?” She included the question mark in her response. She also mentioned the periodic table specifically, but not the elements or atoms represented on it. Her example of a chemical was vinegar because “it has a formula.” The non-example she provided was an apple because “it is living.” Her use of a question mark in the definition suggests she wasn’t sure of her definition. Her reasoning for the example and non-example she provided do not relate to her definition, providing more evidence that she was unclear on what chemicals are or how they may be defined. Another teacher suggested chemicals were “substances made of atoms and molecules.” She said oxygen was an example of a chemical because “it is on the periodic table” and a table was a non-example, though she did not provide an explanation for her non-example. This response both used inconsistent reasoning between her definition and example and included no explanation for her non-example.

Teachers who used consistent reasoning for both the matter and chemicals questions had an average spatial score of 53%. In contrast, the teachers who used inconsistent reasoning for the matter questions had an average spatial score of 37%. The teachers using inconsistent reasoning for the chemical questions had an average spatial score of 44%. While those who used consistent reasoning scored near the group average spatial score of 52%, the teachers who showed inconsistent reasoning scored below the group overall average. On both sets of questions, defining and providing examples for matter and chemicals, teachers who used consistent reasoning in their responses tended to have higher spatial ability on average than teachers who used inconsistent reasoning in their responses.
Discussion

Similar to a related study (Chapter 2), a significant, positive correlation was observed between mental rotation ability and understanding of the particulate nature of matter. However, in contrast to the study in Chapter 2 on middle school students, only one question on the particulate nature of matter assessment showed a significant difference in spatial ability between teachers who chose the correct response and those who chose an incorrect response. While many of the questions in the student study showed a significant difference in spatial ability among response choices, it is likely that the low number of teachers in the current study contributed to the lack of a significant difference in spatial ability by response choice. Readers should use caution in generalizing the item analysis, as the only question on which a significant difference in spatial reasoning between answer responses was found had 16 teachers choosing the correct response and only 4 teachers choosing the incorrect response. The low number of teachers in this study reduces the reproducibility of the study. It is also possible that teachers’ better understanding of the chemistry content led to the lack of the difference. However, it should be noted that some teachers scored as low as 55% on the ParNoMA, which is barely higher than the mean score for the students in the related study. The significant correlation found in this study aligns with prior studies that found significant correlations between spatial reasoning and understanding of chemistry content at the college level (e.g. Pribyl & Bodner, 1987; Wu & Shah, 2003; Stieff, 2013).

The teachers who were able to use consistent reasoning in providing definitions and examples for matter and chemicals had higher spatial reasoning scores than teachers who used inconsistent reasoning. This work also illustrates the need to further examine the chemistry content knowledge of middle school science teachers and the role that spatial reasoning may
play in those understandings. Studies should also examine the impact the chemistry content knowledge and spatial reasoning ability of teachers has on students’ learning outcomes in the middle school classroom.

While not all of the teachers exhibited significant misconceptions related to middle school chemistry concepts, some had trouble defining common terms or applying those definitions. Others also struggled with questions on the written assessment of the particulate nature of matter understanding, suggesting they had a range of understandings similar to what Haidar (1997) found in his study of prospective chemistry teachers. One question on the written assessment was particularly difficult for teachers, with just over half answering it correctly. The question asked which process forms oxygen and hydrogen gases from liquid water. Eleven of the teachers correctly responded decomposition, but other teachers chose vaporization, evaporation, and boiling. Each of these choices involve the change of state from a liquid to a gas. Why did teachers choose the response they did? While the teachers may have had a misconception that the change of state from a liquid to a gas also breaks water apart into hydrogen and oxygen gases, it is also possible that teachers did not understand the vocabulary in the question. Only one teacher incorrectly answered a similar question that asked what the arrangement of molecules would look like when the liquid changed to a gas. The correct image showed the molecules farther apart, but otherwise unchanged; the teacher who answered incorrectly chose an image where the molecules were identical in arrangement to the liquid phase. While not an identical question, the difference between choosing images versus using the correct vocabulary brings to question whether the teachers understand the terms used. In the first question, where many teachers answered incorrectly, they tended to choose one of three similar, incorrect terms. It would be helpful to know why the teachers chose the
responses they did and also whether there would be a difference in responses to identical questions where one used chemistry vocabulary terms and the other used images only. This disconnect on some questions on the ParNoMA combined with the difficulty in using consistent reasoning with definitions and examples of terms suggests that at least some of the teachers have fragmented, explanatory frameworks of the middle school content similar to their students, rather than coherent understandings (Samarapungavan & Wiers, 1997).

Conclusions

One limitation of this work is the lack of information about why teachers chose particular responses on the assessment. Did the teachers who chose the incorrect responses have a misconception, or did they not understand the associated vocabulary? It would also be helpful to have additional middle school science teachers, preferably sampled across a wider area of the country to make a more representative sample. While the teachers in this study performed relatively well on the ParNoMA on average (mean score – 89%), some scored as low as 55% on the assessment. Investigating the background of teachers who scored across the range would also be informative in better understanding where the difficulties come from.

The teachers in this study did well, on average, on the content assessment, but not all of the teachers were able to answer all of the questions on a fundamental concept in chemistry correctly. In this study, a significant, positive correlation was found between mental rotation ability and understanding the particulate nature of matter. The range of teachers’ scores on the mental rotation assessment ranged from 5% to 90%. This range suggests that some teachers may either be learning and then later teaching STEM content despite their poor spatial ability or that their spatial reasoning is an obstacle to understanding the content. Either way, additional work should be done to better understand the role of different spatial abilities in
learning, understanding, and teaching a variety of chemistry and other STEM content. Additional work should also be done to foster the development of preservice and inservice teachers’ spatial reasoning ability. This study has focused on what the teachers know specifically, but further work should be done examining how teachers of different spatial ability and different content knowledge may be impacting their students’ learning of STEM content in the classroom.
This set of manuscripts provides a body of work that begins to examine how spatial reasoning and understanding of chemistry are related in middle schools. The first two papers examine the link quantitatively (Chapter 2) and qualitatively (Chapter 3) for students while the third paper (Chapter 4) examines the relationship for teachers using a mixed-methods approach. It is the first work that examines the link between spatial reasoning and understanding chemistry at the middle school level. Other studies have examined this relationship for STEM fields in general (Wai, Lubinski, & Benbow, 2009) or for chemistry specifically but focused on the university level, with few studies extending to the high school level (e.g. Pribyl & Bodner, 1987; Wu & Shah, 2003; Stieff, 2013). Wu and Shah (2014) called for more work to be conducted in this area at the pre-college level, but their discussion of the matter made it clear that the high school level was the level to which they were referring. However, the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) start listing standards that address fundamental concepts in chemistry as early as the fifth grade, with the middle school standards bringing a consideration of matter at the particulate level to the forefront. In order to understand chemistry, students must learn to describe and understand matter and its interactions at the particulate level; without this understanding of fundamental concepts in chemistry such as the particulate nature of matter (PNM), students are likely to struggle in understanding additional concepts in chemistry (Hesse & Anderson, 1992; Treagust & Chittleborough, 2001; Ahtee & Varjola, 1998; Gabel, 1993; NRC, 2012).
Major Findings and Connections

The data show that spatial reasoning ability (specifically, mental rotation) and understanding of chemistry (specifically, the particulate nature of matter, PNM) are significantly, positively correlated for both middle school students and their teachers. The correlations are significant for students prior to and after receiving instruction in chemistry in 6th and 7th grade. No data was collected in 8th grade classrooms, as chemistry topics were not taught in 8th grade in the schools where this data was collected. The correlation prior to instruction in 6th grade represents what students know prior to formal instruction in chemistry in their school classrooms. While science is taught prior to 6th grade, it is inconsistent; many of the elementary schools in the district where data was collected teach science no more than one hour per week. The post-instruction correlation in the seventh grade represents the end of chemistry instruction in the middle grades. Any formal chemistry instruction after this point will not likely occur until the students enter high school. However, chemistry-adjacent topics are abundant in other science areas which the students will encounter before additional formal chemistry instruction. For instance, 8th grade science standards include geology topics, where students learn about minerals, soil, weathering, weather, and climate. Each of these topics have links to understanding matter. Biology is frequently taken prior to chemistry in high school. Biology topics include osmosis, diffusion, photosynthesis, and cells. Without an understanding of the PNM, it would be difficult for students to understand how each of these work. Talanquer (2008) asserted, “when students learn about atoms they are given the key to unlocking many of the doors across the sciences, in physics, chemistry, biology, and earth science” (p. 18). Given the amount of material in other science topics
that hinge on understanding the PNM but are taught prior to students taking chemistry in
high school, it is imperative that we focus on better understanding the teaching and
learning of the PNM in middle school classrooms. In addition to knowing that spatial
reasoning ability is correlated to understanding the PNM for middle school students, it is
important to know that the relationship is also true for their teachers. While we cannot
infer any causal relationships from a significant correlation, it is important to note the
correlation and explore the relationship further to better understand why the two are
correlated and what that means for the impact of the teachers who fall along the range of
spatial ability.

In examining the student responses on individual questions on the Particulate
Nature of Matter Assessment (ParNoMA; Yezierski, 2003) for students in the 7th grade
post-instruction group, the data show a significant difference among the spatial reasoning
score for students choosing each of the answer responses; this trend held true for 17 of
the 20 questions on the assessment. Also, the average spatial score for students choosing
the correct response tended to be higher than students choosing an incorrect response
choice; this trend held true for 15 of the 17 questions where a significant difference in
spatial reasoning scores was observed. This time point of test data was chosen for item
analysis as the students in this group should have learned all of the material addressed on
the assessment, and incorrect responses may be more likely to be due to misconceptions
or alternative understandings rather than outright guessing as may be the case in groups at
earlier time points. While the data support the hypothesis in that there was a significant
difference in spatial ability by response choice for most questions, the post-hoc tests that
better parsed where the difference truly was, were less conclusive. In some cases, the
correct response was significantly higher than other responses. In other cases, it was only significantly higher than some other responses. In still other cases, the overall significance among answer choices was due to a difference in spatial ability on other incorrect response choices. The teacher data showed a significant difference in spatial ability by response choice for only one question. The low N or the high average score (89%) of the teacher data set may have impacted the lack of significance. Interestingly, unlike the student data where the incorrect choices were more diverse, many of the questions showed that teachers either chose the correct response or a single incorrect response. Compared to the students who chose incorrect responses, the teachers who responded incorrectly seemed to share a single, common misconception relating to that question. In contrast, the students who responded incorrectly to questions varied in their choices. Teachers need to be aware of their own misconceptions about content matter and also work to develop scientifically correct understandings in order to provide quality instruction (Sadler et al., 2013). They also need to be aware that there may be more than one misconception held by students in their classroom and that misconception may be different from one they experienced themselves in the past.

When examining the ways in which the pre-instruction sixth grade students described matter and chemicals, the data showed that the students with lower spatial ability tended to rely on keywords, offering little in the way of explanation or reasoning for their definitions or examples. In contrast, students of higher spatial ability used some keywords, but provided longer explanations or descriptions and were able to apply their reasoning consistently when asked how they knew their examples or non-examples were accurate. Similarly, the teachers who used consistent reasoning in their responses,
meaning their examples and explanations matched their definitions, tended to have higher spatial scores than teachers who used inconsistent reasoning in their responses. Also, both the teachers and the students seemed to have an easier time defining (whether correctly or not) and providing examples for matter than for chemicals. Perhaps part of the problem is that matter is more consistently defined, whether looking in textbooks, dictionaries, or online, than chemicals are. Haxton (2016) recently wrote about a survey conducted by the Royal Society of Chemistry about the public’s perception of chemistry in the United Kingdom. She commented that the survey suggested we need a clear definition of chemical and that we need to be careful about the words we use in teaching about chemicals, yet at the same time, a variety of definitions were presented for the term chemical. Without a clear consensus in the chemistry community about how to define chemicals, is it any wonder that both students and teachers had a difficult time defining or providing examples for the term?

Finally, the teachers’ understanding of the PNM was generally good, with an average score of 89% on the ParNoMA. The particulate nature of matter is a fundamental concept in chemistry, and should be something with which all middle school science teachers are comfortable. While the average score suggests that most teachers understand this content, the lowest score in the sample of 55% correct suggests that some teachers struggle with the concept. This is not far above the average score for students (48.4% at the post-7th grade time point; this is the highest average score for any student group). The range of scores on the Purdue Spatial Visualization Test of Rotations (PSVT) was even wider; teachers answered from 5% to 90% of the questions correctly. Knowing that this study and others have shown a significant correlation
between spatial reasoning ability and understanding chemistry concepts, it stands to reason that we should be concerned about teachers who are scoring on the low end of the spatial reasoning scale. How well do these teachers understand the content they are expected to teach? The poor teacher scores on the ParNoMA also suggest that while it may not be true for all teachers, at least some of the teachers have fragmented frameworks of understanding of middle school chemistry concepts similar to those of their students. Other studies have also shown a significant correlation between spatial reasoning and other areas of STEM (e.g. Wilhelm, Jackson, Wilhelm, & Sullivan, 2013; Grabow, 2003; Pribyl & Bodner, 1987). While this dissertation only measured one spatial reasoning ability (mental rotation) and one area of chemistry (the particulate nature of matter), the low spatial scores of some teachers and the correlations between spatial reasoning and STEM content suggest that we should continue to examine the relationship between spatial reasoning and understanding STEM content for middle school teachers as well as the impact of low spatial ability on teachers’ instruction.

Teachers need to be aware of their own misconceptions as well as those of their students (Sadler, et al., 2013). This awareness includes an understanding of how their own misconceptions may be impacting their students’ learning; if they themselves have misconceptions or incomplete understandings of the topic, they will be unable to teach the content to their students effectively. Teachers simply cannot teach content they do not understand themselves. While the definitions and examples for matter were easier for both teachers and students, both groups struggled with defining chemicals or providing reasonable examples. While those with higher spatial reasoning ability had an easier time, the performance was still quite varied. With respect to teaching students, how can we
expect students to understand what chemicals are when teachers are not sure themselves? But also, are teachers even aware of the ways in which they are discussing matter and chemicals in the classroom? Without a common, clear definition for the term chemicals from the chemistry community, it is likely that a variety of definitions will be used in classrooms, leading to a range of understandings from students who learn in those classrooms.

Rethinking the Chemistry Triad

Throughout this work, Johnstone’s (1991) triangle has been the framework for consideration. His triangle, which incorporates the macroscopic, microscopic, and symbolic levels of chemistry (see Figure 1) has been used by a variety of researchers to frame their work as well. For instance, Gabel (2005) discusses the use of the triangle to guide instructional decisions for chemistry, suggesting that teachers should begin with macroscopic observations, then add sub-microscopic explanations, before moving to the more abstract descriptions at the symbolic level. This framework also appears in the learning progression for matter in the Next Generation Science Standards. The elementary grades focus on the macroscopic, the middle grades begin to include the sub-microscopic (or particulate, as used in the studies presented in this dissertation), and the symbolic is addressed in the high school grades (NGSS Lead States, 2013).

![Johnstone’s triangle](image)

*Figure 5.1: Johnstone’s triangle (1991, p. 78).*
Others have conceptualized this triangle in different ways, including Johnstone himself in his initial 1982 paper on the topic. In that paper, he referred to the corners as descriptive and functional, representational, and explanatory. Essentially, the level at which phenomena are experienced, the level at which they are communicated or represented by signs, and the level at which phenomena are explained (Johnstone, 1982). Johnstone later associated the descriptive and functional level with the macroscopic, or the phenomena that are easily observed and described in our world. He associated the representational level with the symbols and mathematical signs and equations used to communicate about chemistry. Finally, he associated the explanatory level with the sub-microscopic or particulate level. While all three levels are needed to truly understand chemistry, it is a bit confusing to differentiate between the areas at times. For instance, how does one differentiate between the sub-microscopic explanation and the symbols used to represent that explanation? Johnstone also noted that while experts navigate the triangle easily, often blending the areas all at once, novices often get stuck in one corner (usually the macro corner) and struggle to relate the other two corners (Johnstone, 1982; 1991; 1993). If we think about a chemistry course, most likely what will come to mind is the use of symbols and equations to symbolically represent the particulate (sub-micro) level, often without a connection to the macro level. If our students are operating mostly at the macro level of understanding, how can they connect what their teacher is telling them to previous experiences? Without this connection, it is unreasonable to expect that our students would retain the information as part of a scientifically correct conception of chemistry. Rather, as Johnstone (2010) points out, it is likely that the students will either not learn the concepts or will create an alternative conception.
The middle school students in this set of studies seemed to have difficulty connecting the macroscopic experiences to the microscopic descriptions, similar to what others have found in prior studies (e.g. Nakhleh & Samarapungavan, 1999; Nakhleh, Samarapungavan, & Saglam, 2005; Lee et al., 1993). Even after experiencing chemistry units in both sixth and seventh grade, students were able to correctly answer just under half (48.4%) of the questions on the Particulate Nature of Matter Assessment, which asked students to choose a correct particulate-level (sub-microscopic) explanation for the phenomenon in question. The data also showed a significant, positive correlation between performance on the Particulate Nature of Matter Assessment and the spatial assessment, indicating that, in general, students with better spatial thinking ability were better able to provide correct, particulate level explanations for the phenomena on the Particulate Nature of Matter Assessment. Similarly, a significant, positive correlation between understanding the particulate nature of matter and spatial thinking was observed with the middle school teachers as well. Taking this influence of spatial thinking into account, I suggest we return to the 1982 version of Johnstone’s triangle, with some modification for thinking about understanding chemistry.

![Figure 5.2. Johnstone’s 1982 Triangle](image_url)

Rather than thinking of the triangle as an illustration of the levels at which we must view the subject of chemistry, I suggest we think about it as an illustration of
understanding or learning chemistry. First, the corner Johnstone (1982) called *Descriptive and Functional*. In my triangle of understanding chemistry, I term this corner *Experiences*. In this corner of understanding, students can make observations, experience a phenomenon, and describe their observations. The second corner was termed *Explanatory*, which is a term I will borrow from Johnstone’s triangle (1982). While I agree with Johnstone and many others that an explanation is needed at the particulate level to truly understand chemistry (e.g. Nakhleh, 1992; NRC, 2012; Treagust & Chittleborough, 2001), I would argue that the macroscopic explanation is better characterized as part of the explanatory area alongside the submicroscopic explanation as suggested by Talanquer (2011). Unlike Johnstone’s triangle, where the macroscopic and sub-microscopic would be separate corners, in my triangle, the macroscopic *experiences* would be in one corner while both macroscopic and microscopic *explanations* would be grouped together into another corner. Depending on the situation, either a macroscopic explanation or a microscopic explanation would be appropriate. For instance, consider a student trying to explain why mixing baking soda and vinegar resulted in a liquid solution, bubbles, a temperature change, and the evolution of gas. I would consider the microscopic explanation of the rearrangement or the atoms and the description of what was observed macroscopically and the relationship between the two to all be part of the explanation. Johnstone’s final corner in his 1982 chemistry triad was termed *representational*, which was later changed to symbolic in his 1991 paper. I suggest we term this corner *tools for communicating and interpreting*. I include the symbols, symbolic system, representations, and illustrations as Johnstone did, but I would also include mathematics, language, and spatial thinking in this corner. Each of these things
are needed for students to make sense of their experiences and provide explanations of a phenomenon. While spatial thinking may not fit neatly into a levels of representing chemistry, it is essential in a model of the areas of understanding chemistry.

Figure 5.3. Triangle of Learning Chemistry

While the triangle of learning chemistry I suggested is more similar to the chemistry triad Johnstone suggested in 1982, the framers of the NGSS used a learning progression for the standards on matter that more closely matches Johnstone’s 1991 or 1993 version of his triad. Which one is more applicable depends on the situation under consideration. It depends on how you look at chemistry and the pedagogical decisions you need to make. For instance, is the issue a matter of scale (e.g. macro, micro, symbolic) or a matter of understanding (e.g. explanations, experiences, tools for communicating and understanding)? One is more fitting in some situations while the other may be more fitting in other circumstances.

For example, in middle school chemistry, students learn about signs of chemical reactions. They might mix two chemicals, such as baking soda and vinegar, together and make observations. Under Johnstone’s triangle, the students would make macroscopic observations (e.g. a solid was mixed with a liquid, resulting in bubbles and a fizzy sound), create a sub-microscopic description (e.g. the baking soda particles dissolved in the vinegar solution and reacted with the acetic acid molecules, producing carbon dioxide gas, water, and sodium bicarbonate), and perhaps represent the reaction using symbols
(e.g. \( \text{NaHCO}_3 + \text{H}_2\text{C}_2\text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{NaC}_2\text{H}_3\text{O}_2 \)). The student may add more detail to any of these, but the focus is on showing the macroscopic observations, describing what is happening at the submicroscopic level, and creating a symbolic representation; essentially, this shows a single reaction at three different scales. If you consider the triangle I suggested, the student would first describe what they observed or experienced; this level may be similar to the macroscopic level of Johnstone’s triad. The description is likely superficial, noting observations without attempting explanation.

In moving to the next corner of my triangle, both macroscopic and submicroscopic explanations are included. For this reaction, the explanations may include diagrams showing how either particles, molecules, or atoms are interacting during the reaction. They may also include macroscopic explanations, such as a solid was dissolved in a liquid resulting in a liquid and a gas. If the reaction vessel were weighed prior to and after the reaction, the student may have also noted a change in mass in their description of the experience, and offer an explanation of how the atoms in the molecules explain that change. The final corner of the triangle provides information on what tools students used to observe and explain what the phenomenon they experienced. They may have used spatial thinking to consider how the molecules moved around in the solution to react. They may have used mathematics to create a model for how mass was conserved. They may also use symbols to communicate how the atoms were rearranged through a chemical equation. If a teacher’s concern is whether the student can describe a phenomenon using all three levels of representation found in Johnstone’s triangle (and used by many others), then using a framework of macroscopic, submicroscopic, and symbolic is appropriate. If instead a teacher is concerned with how students understand a
phenomenon and whether (and how) they make connections between the macroscopic and particulate levels of chemistry, then perhaps my triangle would be more appropriate.

**Recommendations for Future Work**

As this is the first set of studies to examine how spatial thinking is related to understanding chemistry in middle schools, additional work should be done to further understand this relationship. First, other areas of chemistry and other areas of spatial thinking should be examined. While mental rotation was chosen in this case, there is not an obvious reason why it is related to understanding the particulate nature of matter. Other studies (e.g. Pribyl & Bodner, 1987) have used the Purdue Spatial Visualization Test of Rotations in relation to chemistry content at other grade levels, primarily college. In some cases, mental rotation is considered its own spatial ability while in others it is considered a subset of spatial visualization. It is easier to reason through spatial visualization being connected to understanding chemistry; one must visualize the particles in a reaction in order to reason through what is happening in a chemical reaction. In this description, if mental rotation is a subset of spatial visualization, then it makes sense that it is related to understanding chemistry. But this also begs the question of whether a test of spatial visualization in general would be a better choice for this kind of research. I would argue that future work should include more general tests of spatial visualization in relation to both specific chemistry content (like the particulate nature of matter) and more general chemistry understanding that is appropriate to the middle school level. In this case, using this test of mental rotation is appropriate as 1) it is the test most commonly used in the chemistry literature related to spatial reasoning, 2) it is a test
that others agree measures mental rotation specifically and not another spatial reasoning ability, and 3) it allows for some comparison of results across grade levels.

Similarly, other areas of chemistry should be examined for its relationship to spatial thinking in middle schools. The particulate nature of matter was chosen in this case because 1) it is a fundamental concept in chemistry, 2) the concept is prevalent in middle school physical standards in the NGSS, and 3) an exam already existed that had adequate reliability and validity data for a similar population. However, other fundamental ideas in chemistry are presented in middle school standards as well, such as the conservation of mass, signs of chemical reactions, and thermochemistry. These other areas would be appropriate to explore as well as a more general understanding of middle school chemistry. These would require the development of appropriate assessments for each of these topics. Previous instruments of general chemistry knowledge that were designed for middle school chemistry no longer match the content taught in those grades, since the NGSS were adopted and implemented.

As this set of studies has added information on the relationship between spatial ability and understanding chemistry in early grades, and prior research has shown this correlation also exists in college, another area of research that should be explored is how this relationship may change over time and how it relates to students’ choice in college and/or careers. This study, like many others looking at spatial reasoning and understanding chemistry, used a cross-sectional design, so we are only seeing the relationship at specific time points. First, chemistry units should be designed that intentionally provide spatially rich opportunities where students can learn both chemistry content and build their spatial reasoning ability. Then, longitudinal studies should be
designed where students who receive spatially rich instruction could be compared to those who receive more traditional instruction. Would the students who receive spatially-rich instruction choose STEM careers over other students? Would these students have more confidence in their ability to be successful in STEM courses? This type of study would allow researchers to follow the growth in spatial reasoning ability and also chemistry content knowledge over time for the same group of students. The data in Chapter 2 suggested that the correlation between mental rotation and understanding the particulate of nature may have increased over time, but a limitation of that study was that two different groups of students (6th graders and 7th graders) were used, so no comparisons can be made between grade levels.

For both the students (Chapter 2) and teachers (Chapter 4), the spatial ability of people who chose each possible answer for individual questions was compared to identify whether there was a difference. While a significant difference was found in spatial ability for students choosing different answer responses on 17 out of 20 questions on the Particulate Nature of Matter Assessment, a similar difference was only found on one question for the teachers. The teacher sample had a much lower N, which likely contributed to the lack of significance. Within the student sample, the average spatial ability of students who chose the correct response was often (but not always) higher than the average spatial ability of those who chose incorrect responses. Further studies should examine this difference, particularly whether there is a difference in spatial ability between students choosing a scientifically correct response compared to common misconceptions. Future work should also include a closer examination of how the instrument is performing for this population. An analysis of whether the difficulty of the
questions matches the ability of the students would be beneficial. It would also be helpful to know whether there is a difference between questions that are text only and questions that include pictures or diagrams. Similarly, the Particulate Nature of Matter Assessment and other chemistry instruments under consideration for use, particularly with middle school students, should be examined for appropriate vocabulary. For instance, do middle school students understand the difference between vaporization and evaporation? In general, understanding more about why students chose (or avoided) particular responses would be enlightening. Better understanding why students with different spatial abilities chose item responses differently could contribute to understanding student misconceptions. Students in this study who chose correct responses tended to have higher spatial ability than students who chose incorrect responses; this difference suggests training spatial thinking along with science content in middle schools could help students better understand chemistry concepts.

As we continue to examine factors affecting what middle school students learn about middle school chemistry, we need to consider the role of teachers. The teachers in this study on average performed well on the Particulate Nature of Matter Assessment, though some teachers scored as low as 55%, which was just above the average for the highest scoring group of students (post-instruction 7th grade students scored 48.4% on average). Similar to the students, more information is needed about why teachers chose certain responses and also how the instrument performs for this population. Future studies should also examine what teachers understand about chemistry more broadly as well as the role of spatial thinking in that understanding. One reason to
examine broad chemistry knowledge is to better assess whether teachers are aware of common misconceptions, both their own and those of their students. Sadler et al. (2013) highlighted the necessity of teachers’ awareness of their students’ misconceptions, saying “Teachers who know their students’ most common misconceptions are more effective than teachers who do not. This particular component of PCK [pedagogical content knowledge] may allow teachers to construct experiences, demonstrations, experiments, or discussions that make students commit to and then test their own ideas” (p. 1043). If the teachers have misconceptions themselves, they may inadvertently pass those on to their students as well. Future studies should examine how teachers’ spatial ability or understanding of the particulate nature of matter impact their students’ learning of chemistry. Another reason to examine teachers’ broad understanding of middle school chemistry is that a broad understanding of chemistry helps teachers make connections between chemistry topics and also between chemistry and other science topics in their classroom. Unlike prior standards that were focused on pieces of knowledge students were expected to learn, the NGSS includes performance expectations, science and engineering practices, and crosscutting concepts. While teachers can point out the crosscutting concepts listed in the NGSS related to performance expectations they are addressing in their classrooms, without a broad understanding of chemistry they may struggle with explaining how the topics are connected to one another. Similarly, teachers need to understand what chemistry is and what chemists do in order to bring the science and engineering practices to life in their classrooms.

One area where the teachers in the study in Chapter 4 struggled was in defining and providing examples for the terms chemical and matter. While teachers with higher
spatial reasoning ability tended to use more consistent reasoning in defining, providing examples and non-examples, and explaining their reasoning, the responses were quite varied. It likely does not help that a common definition of *chemicals* is difficult to find. How is this variation impacting their students? In the case of the term *chemicals*, similar to other poorly understood scientific terms, students hear the term used in a variety of ways in the media, many of which are not scientifically correct. We need to examine not only how teachers understand chemistry terms but also how they are using them in the classroom. Are teachers using scientific terms in the classroom consistently? The presence of common misconceptions and difficulty in providing examples or using consistent reasoning suggests that some teachers may have fragmented explanatory frameworks similar to their students.

The gaps in knowledge exhibited by some of the chemistry teachers are not surprising. Prior to the NGSS, middle school science teachers could spend their careers teaching only one science, depending on the grade level they taught. The NGSS, however, is arranged so that middle school teachers teach a variety of science content in each of the grades; the teachers are no longer able to stick to a single science subject. Instead, they are expected to be able to teach all science content areas at the middle school level and be able to make connections between areas. If teachers were licensed based on a degree in a single science content area, then it is no wonder they would have gaps in their science content knowledge. For instance, if teachers took few or no chemistry classes they may be unaware of the subtle differences between boiling, evaporation, and vaporization. They may also similarly struggle with understanding what chemicals are or how to define them well. Teachers may also have a surface knowledge of chemistry, but lack the deep content knowledge to apply a definition or make
connections between topics. Knowing that spatial thinking is related to their content knowledge, teacher educators need to not only address gaps in content knowledge but also the development of spatial reasoning skills. Also, teachers need to be aware of how to foster the development of spatial thinking within their classrooms. This begs the question: are we sufficiently preparing middle school science teachers for teaching in current and future classrooms?

**Conclusions**

This dissertation includes the first studies to examine the relationship between spatial thinking and understanding of chemistry content at the middle school level. It includes an examination of this relationship for both students and their science teachers. While significant, positive correlations between mental rotation and understanding of the particulate nature of matter were observed, the correlations alone do not explain how or why the two are related. It is important to establish the relationship exists at the middle school level in addition to the college and high school level, which other studies have addressed. This set of studies addressed a gap in the literature, which was highlighted by a combination of Wu and Shah’s (2003) meta-analysis of the spatial literature in chemistry where they called for additional work to be done at the pre-college level and also the implementation of the Next Generation Science Standards (NGSS Lead States, 2013), which include fundamental ideas in chemistry starting at the middle school level. These two combined suggested a need for the examination of spatial thinking and understanding of this chemistry content at the middle school level. While additional work is needed, this dissertation established that a basis for future work in the area of spatial thinking in middle school chemistry.
Appendix A

Next Generation Science Standards for the Particulate Nature of Matter: Physical Science

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<th>NGSS Performance Expectations in Physical Science</th>
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NGSS Lead States, 2013
## Appendix B

### Next Generation Science Standards for the Particulate Nature of Matter: Other Sciences

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*NGSS Lead States, 2013*
Appendix C
Example Lesson - What happens to the mass?

Students predict and test whether the mass will change in chemical reactions. Students also model the substances prior to, during, and after a chemical reaction; both the macroscopic views and the particulate views are included. Students are also asked to consider how the two views are related. This lesson addresses the NGSS performance expectation MS-PS1-5 Develop and use a model to describe how the total number of atoms does not change in a chemical reaction and thus mass is conserved (NGSS Lead States, 2013, p. 56). An emphasis is placed on relating the macroscopic (i.e. the things we can measure or observe, like mass) and the particulate views (i.e. the atomic/molecular/ionic/etc. level we can only model), which helps students make the connection between conserving the number of atoms and the mass in a chemical reaction.

Engage:

1. For each of the following, ask students to identify whether it’s a chemical or physical change and also predict what will happen to the mass of the materials: increase, decrease, stay the same. Be sure to weigh each and record the mass before and after each demonstration.
   a. Tear a piece of paper into 8 pieces.
   b. Place alka-seltzer into a glass of water.
   c. Melt an ice cube.
   d. Toast a marshmallow over a flame.
2. Ask students if the results were what they expected. Ask for reasons for their answers.

3. Ask students to create models (most likely, draw diagrams) showing what happened in each case. Be sure to include both the macroscopic (what we can sense) and the particulate (particles/atoms/ions/molecules) views.

4. Share the quote, “We may lay it down as an incontestable axiom that, in all the operations of art and nature, nothing is created; an equal amount of matter exists both before and after the experiment. Upon this principle, the whole art of performing chemical experiments depends.” – Antoine Lavoisier, 1789
   
a. Discuss what this quote means.
   
b. The quote is one of the early statements of the Law of Conservation of Mass.

Explore

1. After hearing/reading the quote, ask students if they think their predictions for part 1 should change.

2. Ask students to revisit their drawings, making changes as needed. Rather than getting rid of any initial models, students should modify or create new models.

3. Based on Lavoisier’s quote (and the Law of Conservation of Mass), we know that the mass should be the same before and after a chemical or physical change. Why might some of the masses from part 1 change? What could be done differently so the masses wouldn’t change?
4. Ask students to choose one of the options below as the best way to confirm the Law of Conservation of Mass. Ask for justification of their choice. (Procedures for each option are listed at the end of the lesson)

   a. Option A: A beaker contains baking soda. A second beaker contains vinegar. Each of the beakers and their contents are weighed separately. The baking soda is poured into the beaker with the vinegar. After the reaction subsides, the two beakers and their contents are again weighed. The masses before and after the reaction are compared.

   b. Option B: A plastic bottle contains vinegar. A test tube contains baking soda. Both containers and their contents are weighed. The baking soda is poured into the bottle. After the reaction subsides, the bottle and test tube and their contents are again weighed. The masses before and after the reaction are compared.

   c. Option C: A beaker contains baking soda. A second beaker contains vinegar; this beaker is covered by a watch glass. Each of the beakers and their contents are weighed separately. The baking soda is poured into the beaker with the vinegar, which is then covered by the watch glass. After the reaction subsides, the two beakers and their contents are again weighed. The masses before and after the reaction are compared.

   d. Option D: A plastic bottle contains vinegar; the bottle has a screw-on cap. Baking soda is carefully wrapped in thin paper. Both containers and their contents are weighed. The bottle is placed on its side without spilling the vinegar. The wrapped baking soda is placed inside the neck of the bottle,
without touching the vinegar. The cap is carefully screwed onto the top of the bottle. The bottle and contents are carefully weighed. The bottle is tipped up, and a reaction occurs. After the reaction, the bottle and its contents are again carefully weighed. The masses before and after are compared.

5. Have students try out the option chosen and respond to the following questions.

Remind them to carefully record the masses and follow the procedures.

a. Were you able to confirm the Law of Conservation of Mass? Why or why not?

b. What happened to the vinegar and baking soda in the option you chose? What about the particles inside of each? Draw a diagram to help with your explanation.

c. Would a different option be better? Why or why not?

d. NOTE: if students did not confirm the Law of Conservation of Mass and decide another option is better, have them try out the new choice if time permits. If there isn’t time, have students discuss as a class what they learned from each option and come to a consensus on which was the best choice.

Explain

1. Ask students to share their results with the rest of the class.

a. Discuss open and closed systems

b. Identify each of the options (A, B, C, D) as an open or closed system.
2. Show students the equation for the reaction between vinegar and baking soda.

3. Have students draw what happened including both the macroscopic and particulate views, now using the specific atoms and molecules.

Elaborate

1. Have each student choose a physical change or a chemical change that was demonstrated in the introduction to this lesson.

2. Ask students to design an experiment to confirm that mass was conserved during the change.

3. Have students write a letter to a family member describing their experiment and explaining why and how it would confirm the Law of Conservation of Mass.

Evaluate

1. Have students trade letters with a classmate.

2. Ask each to read their classmate’s letter, think about whether there is enough detail to understand the experiment, and decide whether they think their experiment will work or not. Ask for reasons, including drawings of the macroscopic and particulate views where appropriate.

3. Ask students to share suggestions to their classmate’s letter, revising their own letters as appropriate.

4. Have students share what they learned with the class. What conditions are necessary for confirming the conservation of mass in a chemical or physical
change? How do the macroscopic and particulate views of the reactions help us understand what’s happening in a reaction or change of state?

Procedures:

Option A:

1. Measure out 5mL vinegar into one beaker and 1.5 g baking soda into a second beaker.
2. Weigh each beaker (and its contents). Record the masses.
3. Carefully pour the baking soda into the beaker containing the vinegar.
4. Observe as the reaction occurs.
5. Weigh each beaker again (and its contents). Record the masses.

Option B:

1. Measure out 5mL vinegar into the empty plastic bottle and 1.5 g baking soda into a test tube.
2. Weigh the bottle (and its contents). Weight the test tube and its contents. Record the masses.
3. Carefully pour the baking soda into the bottle containing the vinegar.
4. Observe as the reaction occurs.
5. Weigh the bottle (and its contents). Weight the test tube. Record the masses.

Option C:

1. Measure out 5mL vinegar into one beaker and 1.5 g baking soda into a second beaker.
2. Cover the beaker that contains vinegar with a watch glass.
3. Weigh each beaker (including its contents and the watch glass). Record the masses.

4. Carefully pour the baking soda into the beaker containing the vinegar. Immediately cover the beaker with the watch glass.

5. Observe as the reaction occurs.

6. Weigh each beaker again (and its contents and watch glass). Record the masses.

Option D:

1. Measure out 5mL vinegar into the empty plastic bottle and 1.5 g baking soda into a test tube.

2. Carefully pour the baking soda onto the middle of a kim-wipe. Roll the kim-wipe up like a burrito. You may need to ask your teacher for help.

3. Weigh the bottle (and its contents and cap). Weight the kim-wipe and its contents. Record the masses.

4. Carefully tilt the bottle onto its side without spilling the vinegar. Place the kim-wipe into the neck of the bottle, careful to not let it touch the vinegar. Carefully screw the lid on the bottle.

5. Weigh the bottle and contents. Record the mass.

6. Tilt the bottle up so the kim-wipe (and baking soda) mix with the vinegar. You may want to swirl the bottle a bit to help them mix.

7. Observe as the reaction occurs.

8. Weigh the bottle (and its contents). Record the masses.
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2015  Kappa Delta Pi (Education Honor Society)
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2008  National Science Teachers Association New Teacher’s Academy Fellow
2004  Alpha Chi Sigma Scholarship in the Chemical Sciences, University of Iowa
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2000  Published in The National Dean’s List
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