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Developing Spatial Reasoning Skills in General Chemistry Students

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**DEVELOPING SPATIAL REASONING SKILLS IN GENERAL CHEMISTRY
STUDENTS**

Dissertation Presented

by

DEBORAH L. CARLISLE

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
Of the requirements for the degree of

DOCTOR OF EDUCATION

May 2014

Math, Science and Learning Technology

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DEVELOPING SPATIAL REASONING SKILLS IN GENERAL CHEMISTRY
STUDENTS

A Dissertation Presented

by

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DEDICATION

This dissertation is dedicated to my brother, Don D. Carlisle.
Thank you.

ACKNOWLEDGEMENTS

I would like to extend my sincere thanks and gratitude to my both of my dissertation advisors, Dr. Kathleen Davis and Dr. Martina Nieswandt. To Dr. Kathleen Davis, for helping me to gain a deeper sense of qualitative analysis, and for helping me to learn how to quantify my qualitative data. Dr. Davis, I also want to thank you for providing me with the rich learning opportunities, which came from my involvement in the NOYCE seminar with the master teachers and teaching fellows. To Dr. Martina Nieswandt for sharing her extensive expertise and insights which allowed me to carefully analyze my data and to consider the significance of my results from a broader lens. Thank you also Dr. Nieswandt for supporting me as I navigated through some challenging times. Both of you helped me to develop into a more thoughtful and critical researcher. I was fortunate to have both of you to advise me.

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mentor to my students. I extend my sincere thanks and appreciation for helping me to grow as a scholar, researcher, and writer.

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you for instilling your love of chemistry and a desire to understand the details. I know you always want what is best – thank you. This degree is for all of us!

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To all of my friends who offered their encouragement and support during this endeavor a sincere “Thank you!” We can now spend some time together – finally.

ABSTRACT

DEVELOPING SPATIAL REASONING SKILLS IN GENERAL CHEMISTRY STUDENTS

MAY 2014

DEBORAH L. CARLISLE, B.S., UNIVERSITY OF NEW HAMPSHIRE

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The study of organic chemistry requires the understanding and use of spatial relationships, which can be challenging for many students. Prior research has shown that there is a need to develop students' spatial reasoning skills. To that end, this study implemented guided activities designed to strengthen students' spatial skills, with the aim of preparing students for organic chemistry and other future STEM courses. Students, taking the second semester of a two-semester general chemistry course, engaged in these activities. This study followed a quasi-experimental design, in which the experimental (n = 209) and the control group (n = 212) were administered a pre-test. Students voluntarily chose to participate in one, two or three activities during their laboratory periods. At the completion of the semester, both groups participated in a post-test designed to measure spatial skill acquisition. The results show that the mean score rose in the experimental

group after each successive intervention. A one-way ANOVA confirmed that student performance differed significantly between the three interventions and the control group. When disaggregating post-test results by gender, male and female students showed approximately the same overall mean score improvement.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS.....	v
ABSTRACT	viii
LIST OF TABLES.....	xiv
LIST OF FIGURES	xv
CHAPTER	
I INTRODUCTION.....	1
A. Spatial Skill Acquisition.....	1
B. Statement of Problem	2
C. Overview of Study	4
D. Purpose Statement	4
E. Research Question	5
F. Scope and Significance of the Study	6
G. Definition of Terms	7
H. Establishing Trustworthiness	8
II LITERATURE REVIEW	9
A. Summary	9
B. Defining Spatial Ability	10
C. Understanding Spatial Ability	11
D. Spatial Ability and Chemistry	13
1. Suggestions for Teaching	14
E. Improving Spatial Ability	15
1. Spatial Training Studies.....	15
2. Reasoning with Spatial Information	17
3. Expert/Novice Distinctions.....	18
4. Learning Chirality and Isomerism	19
F. Cognition and Spatial Reasoning in Chemistry	21

1. Organizing Principles	21
2. Brain-sight	23
3. Information Processing Model	23
4. Spatial Working Memory	25
G. Johnstone's Model of Chemistry Learning	25
H. Developing Spatial Skills in Chemistry	28
1. Influential Learning Theories	29
a. Constructivism	29
b. The Models and Modeling Paradigm	31
c. Theoretical Framework	32
III METHODS AND PROCEDURES	36
A. Introduction	36
B. Research Question	37
C. Problem Statement	37
D. Research Design	38
1. Participants and Setting	40
2. Quantitative Instruments	42
3. Qualitative Methods	45
a. Field Notes	45
b. Interviews	46
c. Artifacts	47
4. Procedure	47
a. Interventions	47
E. Data Analysis	51
1. Quantitative Data Analysis	52
2. Qualitative Data Analysis	54
a. Analysis of Field Notes	55
b. Analysis of Interviews	58
c. Analysis of Artifacts	59
3. Aligning Data	60
F. Reliability and Validity	60
G. Gaining Entry and Informed Consent	61
1. Gaining Entry	61
2. Informed Consent	62

a. Confidentiality	62
H. Researcher Profile	62
IV RESULTS.....	64
A. Post-Test Results	64
B. Improved Skill Areas.....	66
1. Identification of Molecular Symmetry Planes.....	68
a. Perspective Taking.....	70
b. Sketching Molecular Models	74
c. Manipulating Models.....	75
d. Identifying Symmetry Plane(s)	76
2. Visualizing Molecules	80
a. Bilateral vs. Vertical Comparisons	80
b. Cyclic Structures	83
c. Comparisons Using 2D Sketches and Molecular Models	84
d. Visualizing Rotations with Molecular Models.....	88
e. Visualizing and Mental Imagery	92
3. Translation between 2D and 3D	95
a. Post-Test Data for Translation Skills.....	95
b. Experiences with Translation Activities	96
i. Intervention One	97
ii. Intervention Two.....	98
iii. Intervention Three	100
V DISCUSSION	103
A. Research Objective.....	103
B. Overview	104
C. Interpretation	105
1. Sketching: Making External Representations.....	106
2. The Importance of Identifying a Symmetry Plane	107
3. Visualization of Molecules	110
a. Molecular Comparisons.....	111
b. The Number of Rotations	112
c. Gesture	112
d. Post-Test Findings	113

4. The Role of Translation.....	114
5. A Model for Spatial Skill Development.....	117
a. Sketch: Making a 3D Representation	119
b. Translate: Interpreting External Representations	119
c. Molecular Models	120
d. Visualize: Constructing Internal Representations	121
6. Additional Findings	122
a. Identified Misconceptions	124
D. Implications	125
E. Strengths and Limitations	128
F. Future Research.....	129

APPENDICES

A. PRE-TEST	131
B. POST-TEST	132
C. TEST ITEM ANALYSIS	133
D. INTERVENTION ONE	135
E. INTERVENTION TWO	138
F. INTERVENTION THREE	141
G. INTERVIEW QUESTIONS.....	144
H. INFORMED CONSENT FORM	147
REFERENCES	148

LIST OF TABLES

Tables	Page
3.1 Participant Numbers	41
3.2 Descriptions of Intervention Activities	51
4.1 Post-Test Scores.....	65
4.2 Post-Test Score by Intervention	65
4.3 Test Items: Analyzed and Grouped According to Skill Focus	67
4.4 Field Notes by Intervention and Theme	71
4.5 Field Note Frequency of Important Observations	73
4.6 Frequency of Re-sketching Attempts in Artifacts	77
4.7 Interviews: Informants and Themes	79
4.8 Frequency of Correct Response to Question 3a) and b).....	86

LIST OF FIGURES

Figure	Page
2.1 Information Processing Model	24
2.2 Johnstone's Levels of Chemistry Knowledge	26
3.1 Data Collection Sources and Dates	40
3.2 Example of Purdue Spatial Visualization Test	42
3.3 Examples of Pre-test Content Questions	44
3.4 Open Coding Notes: Looks Different (LD) and Models Help (MH)	56
3.5 Example of Axial Coded Notes for MH with Rotation	56
3.6 Intervention 3: Student Rotational Sketches	57
3.7 Coded Note Suggesting Molecules are Static	58
4.1 Post-Test Results by Item	65
4.2 Symmetry Plane Questions: with and without 3D image	68
4.3 Skill Progression of Intervention Activities	69
4.4 Symmetry Plane Sketches: Examples of Student Work	76
4.5 Student Free Hand Sketches with Symmetry Planes	78
4.6 Rotation of Molecular Structure	80
4.7 Bilateral vs. Vertical Comparison	82
4.8 Molecular Comparisons with Cyclic Structures	83

4.9 Comparison of Molecular Structure	84
4.10 Student Sketch of the Rotation Steps for Question 3a)	87
4.11 Interview Questions 5 and 6a)	90
4.12 Interview Question 1, Lewis Structure for CH ₂ F ₂	92
4.13 Translation from 3D Model Picture to Sketch with Cues.....	96
4.14 Dash/Wedge Representation of Methane	97
5.1 Use of Dot Matrix Paper to Enhance the Meaning of Dash/Wedge Cues.....	110
5.2 Model for the Development of Chemistry Students Spatial Skills.....	117

CHAPTER I

INTRODUCTION

A. Spatial Skill Acquisition

Spatial reasoning ability has long been recognized as an important skill in the science, technology, engineering and math (STEM) disciplines (Davidowitz & Rollnick, 2011; NSB, 2010; Sorby, 2009; Stieff, 2007). In fact, spatial reasoning ability has been a good indicator of the choice of a STEM major or STEM career (Ferguson, 2008; Sorby, 2009). The improvement of STEM education has been recognized nationally, as an important goal (NSB, 2010), meta-analytic studies show that a small percentage, less than one quarter of all students have the spatial skills necessary to succeed in early STEM coursework (Uttal & Cohen, 2012; Wai, Lubinski, & Benbow, 2009), making the teaching of spatial skills important in recognizing this goal. Specific cognitive aspects of spatial reasoning have been studied in fields such as engineering, architecture, physics and chemistry. Research findings suggest that spatial reasoning ability is a characteristic common to mathematically gifted individuals in STEM fields (Weckbacher & Okamoto, 2012). Research has also shown that spatial ability can be improved upon with training (Coleman & Gotch, 1998; Harle & Towns, 2011; Sorby, 2009; Stieff, 2007; Terlecki, Newcome, & Little, 2008).

In the spirit of discipline based education this study seeks to specifically improve general chemistry instruction to deliberately teach spatial skills to students (NRC, 2012). The curriculum units used in this study were developed by carefully assessing the fundamental skills that students would need to understand core chemistry content. Based on data collected from a previous pilot study (Carlisle, 2012), in a year-long organic

chemistry course, these skills were determined to be 1) visualization, 2) sketching/representation, and 3) translation between 2D sketches and 3D models, of molecules and their interactions. For the development of these activities general course content was viewed from a broad lens to determine which topics made the best connections for spatial skill acquisition. These topics were determined to be VSEPR Theory, intermolecular forces, solid state, solutions, kinetics, and thermodynamics, because these areas have specific conceptual application to spatial reasoning in chemistry. Although many skill development activities could potentially be stand alone exercises to foster sketching, visualization, and translation abilities, it is through the effective integration of these skills to the course content that students will understand the relevance of improving their own spatial skills. Certainly, these skills will also enhance student performance in many related science courses, by allowing them to assess concepts requiring sketching and visualization in 3D.

B. Statement of the Problem

For the vast majority of students spatial ability is learned and developed through life experiences (Harle & Towns; 2011, Wai, 2009). Often the details of spatial properties are not explicitly taught to students, and therefore students' interpretation of important conceptual information is based on their own assumptions leading to misconceptions or incomplete understanding (Carlisle, 2012). Based on my idiosyncratic knowledge it appears that spatial information is often implied, because it is embedded in abstract content that is complex, but oversimplified for a variety of reasons. The first, being the rapid pace at which a large amount of conceptual material is covered. Secondly, that spatial concepts are not adequately recognized to require teaching, because it is assumed

students “pick it up” the necessary information by observing or visualizing. The acquisition and development of spatial reasoning skills requires explicit teaching, this will allow all students a much better opportunity to learn (Sorby, 2009). Improvement of spatial understanding will allow a larger percentage of students to be successful in STEM disciplines (Wai, 2009). It is recognized that the small percentage of students who have special talent, life experiences, or prior knowledge, which predisposes them to consider spatial information, have a significant advantage when it comes to making connections and recognizing the deeper significance of conceptual information (Uttal & Cohen, 2012, Wu & Shah, 2004). It is also possible that improved learning of spatial reasoning will lead to a broader conceptual understanding, which may allow for more creative and innovative thinking within the discipline (Ramadas, 2009).

Many disciplines including engineering, physics, mathematics, molecular biology, chemistry, or architecture require students to have the ability to reason with spatial information. In fact, student success in virtually all of the STEM disciplines is influenced by spatial ability (Davidowitz & Rollnick, 2011; Sorby, 2009; Stieff, 2007; Wai, 2009). It seems that students who don't receive explicit training or practice with spatial reasoning are disadvantaged in successfully completing advanced science course work and as a result may be more likely to drop out of STEM fields (NSB, 2010; Uttal & Cohen; Wai, 2009). Considering the continuing increase of jobs within STEM disciplines, it seems important to provide all students with opportunities to access these; developing and increasing their spatial ability is one important step towards this goal.

C. Overview of Study

This mixed methods study implemented and evaluated guided activities designed to develop and strengthen general chemistry students' spatial reasoning skills. The quantitative strand of this study analyzed students' performance on a post-test requiring the use of spatial knowledge. Post-test analysis allowed the experimental and control group's performance to be compared. The qualitative strand of this study relied on field note observations, interviews and artifacts to capture student thinking, questions, and progress as they participated in the guided activities. The thesis of this study was that students' spatial skills would improve as a result of being involved in the spatial intervention. This study provides insight into the ways in which we can improve students' spatial skills in chemistry, it also provides guided activities designed for this purpose, as well as pre and post-tests which may be useful in future test design.

D. Purpose Statement

The ultimate goal of this research is to assist undergraduate chemistry students in the development of their spatial reasoning skills, allowing for a broader range of students to acquire these important skills and prepare them for advanced chemistry course work. To accomplish this, an intervention was carried out using molecular models to allow students to 1) sketch, 2) visualize, 3) translate and 4) explore molecular interactions. Additionally, this study seeks to gather data about how to best support student learning of these important skills, so that the spatial aspects of chemistry becomes more accessible. Descriptive qualitative data gathered during this study will be used to inform instruction

for teaching spatial reasoning skills, including how to make them meaningful in large lecture setting.

This research has the potential 1) to further the understanding of how students acquire spatial reasoning skills in general chemistry, 2) to use this group of chemistry students as a base-line reference for understanding what facets of spatial reasoning other groups of chemistry students may find useful, and 3) to suggest teaching strategies to support spatial reasoning in general chemistry courses for high school and undergraduate students. Overall, this study will inform pedagogical practice in general chemistry, with the aim of improving a broader range of student understanding among a diverse group of learners.

E. Research Question

Based on the purposes of this study the following research question was appropriate: In what ways does a spatial intervention support students' learning of spatial reasoning skills?

As there have not been specific studies with in undergraduate science, and more specifically within the discipline of chemistry, which describe successful approaches to student learning of spatial skills, this question allows for a broad exploration of the ways in which the intervention activities supported student skill acquisition. Qualitative data will provide authentic descriptions of the ways in which the intervention helps students to acquire spatial reasoning skills. Specifically addressing how students develop their understanding of spatial applications in chemistry. This data will provide useful insight for the further development of these skills. The research question also allows the researcher to employ quantitative data collection methods that could illuminate how well

students are able to transfer their understandings. This question was viewed through the lens of the Constructivist Theory, which was enhanced by the Models and Modeling Framework and cognitive psychology to better understand how students were constructing their knowledge.

F. Scope and Significance of this Study

This study is a follow-up to a pilot study that took place during the fall 2011 and spring 2012 school year at a large research institution in the northeast U.S. with a small group (n = 28) of chemistry majors enrolled in organic chemistry. This study sought to better prepare students by developing their spatial reasoning skills prior to taking the organic chemistry sequence or future STEM course work. The second semester of general chemistry was chosen for these skill-building activities, as it was the semester preceding organic chemistry, and it could be assumed that students' would have already acquired some spatial knowledge of molecules, during the fall term, from which to build.

This study is significant in that it provides an analysis of how students' acquire the skills needed to visualize, sketch, and translate spatial information required for reasoning about molecules. Hegarty (2012) emphasizes the importance of training students in the use of external visualizations such that they can accurately interpret the information as represented and employ it for successful problem solving. Students in this study received training to support them in the use of external visualizations, while also learning how spatial understanding deepens their conceptual knowledge.

This study was particularly interested in teaching students how to efficiently compare molecular structures, visually or through the use of a manipulative. Emphasis

was also placed on the representational skills required to accurately sketch molecular structures from either the “minds eye” or from a 3D molecular model. The application of these skills is recognized to be important in the development of spatial reasoning in a wide variety of STEM disciplines, including chemistry (Gilbert, 2005; Harle & Towns, 2011; Stieff, 2007).

G. Definitions of Terms

1. Analytic method: a logical stepwise approach that simplifies the need to reason with spatial information.
2. Chiral: a type of molecule that has a non-superimposable mirror image. Molecules that are chiral contain asymmetric carbon atoms.
3. Conformation: is the 3-D shape and arrangement of the molecule in space
4. Dash/wedge: notation used to denote the spatial arrangement of atoms in 2-D representations. The dash represents behind the plane and the wedge represents toward the viewer, or out in front of the plane.
5. Isomer: compounds with the same molecular formula, but different structural formulas.
6. IUPAC: international union of pure and applied chemistry, common world language of chemistry
7. Methyl groups: is a CH_3 group or a carbon with 3 hydrogen atoms connected to it.
8. Reaction Mechanism: is a proposed step-by-step sequence of elementary reactions by which chemical change is thought to occur.
9. Stereochemistry: an area of chemistry that involves the relative spatial arrangement of atoms that form molecules. It looks at the structure and the manipulations of molecules. Chiral molecules are an important branch of stereochemistry.
10. Stereoisomer: isomers with the same molecular formula, and sequence of bonded atoms, differing only in the 3-D orientations of their atoms in space.
11. Symmetry: evenness and proportionate balance of a molecule. Leonardo's Vitruvian Man (ca. 1487)

12. Symmetry planes: a three dimensional object's symmetry axis. A directional line through an object that preserves even distance in many directions.

13. Zig-zag notation: a short hand method organic chemists use to represent the carbon chain or backbone. Each line represents one carbon bonded to another.

H. Establishing Trustworthiness

To address qualitative validity and reliability, the researcher established trustworthiness in several ways:

1. Triangulating: Multiple data collection methods were used to collect data at various time points. Data analysis utilizes a mixed methods approach to incorporate the data from various sources.
2. Peer Review: The researcher engaged in conversation with two critical friends who are both experienced chemical educators (Rossman and Rallis, 2012, p.65). These friends shared in tentative hypothesis formation, and early emerging ideas.
3. Establishing Prolonged Engagement: The researcher was present for an extended period of time in the setting, repeatedly working with the participants, allowing for more than a snapshot view (Rossman and Rallis, 2012, p. 65).
4. Participant Validation: Interview notes were shared with the participants, allowing them to correct, and elaborate on the findings prior to analysis.
5. Artifacts: Student work was collected during the interventions, so that the researcher could make a direct reference to sketches and diagrams that students made.
6. Developing an Audit Trail: Data collection sources are well documented allowing for "outside researchers" to assess the validity of the researchers findings (Merriam, 2009, p.211).

CHAPTER II

LITERATURE REVIEW

A. Summary

To begin, I will first define the meaning of spatial ability as it was used in this study, acknowledging that it is a complex construct. Several studies, spatial ability tests, and a recent literature review are used to explain how we have come to develop an understanding of spatial ability. Next, developing spatial ability is discussed as it relates specifically to chemistry. This discussion highlights previous studies and includes some strategies used to teach spatial information explaining the impact they had on student learning. In order to better understand how spatial skills are acquired a few aspects that relate to the cognition of spatial information are discussed. A landmark paper in chemical education by Alan Johnstone is used to frame learning within the discipline of chemistry. In this paper, Johnstone considers and explains the learning difficulties arising for students new to the study of chemistry (Johnstone, 2000). Research addressing the improvement of spatial ability is discussed along with some suggestions for developing the spatial abilities of students. Throughout the review the significance of chemistry students developing spatial reasoning skills is highlighted. Lastly, the need for studies in this area is presented, and key pieces of literature that were helpful in developing the spatial intervention activities are explained. The literature review ends by discussing the key learning theories that guide this research, which follows into the theoretical frame that is used to address my research question.

B. Defining Spatial Ability

In a recent review of the spatial ability literature, by Harle and Towns (2011) spatial ability was defined by Lohman, (1979) as the ability to generate, retain, and manipulate abstract visual images. Additionally, it calls upon students to contrast mental images to real images. These real images may be represented by hand-held molecular models, 2D representations, or images developed by computer renderings. At the most basic level, spatial thinking requires the ability to encode, remember, transform and match spatial stimuli (Lohman, 1979 p. 127). In attempting to understand this cognitive ability, Lohman's meta-analytic study identified three major factors (Harle & Towns, 2011):

- (1) Spatial relations – requires spatial rotation of an object in a plane 2D, or out of a plane 3D*
- (2) Spatial orientation – ability to imagine how an object would look from a different perspective*
- (3) Visualizations – require movement or displacement of parts of a spatial figure. This aspect is considered the most complex.*

The cognitive factors listed in (1) and (3) above require further delineation to make the distinctive features clear. Spatial relations (1) relates to “speeded” rotation which takes into account the amount of time required to match a target orientation, while visualization (3) requires the movement or displacements of parts of a spatial figure relative to other parts of the figure. These three major factors identified by Lohman were further supported by a second meta-analysis done by Carroll (1993).

C. Understanding Spatial Ability

Historically, there has been some debate about whether spatial abilities can be effectively enhanced through teaching or whether they reflect an innate skill possessed by individuals. The early quantitative measures initially used to assess spatial skills

actually fueled this debate. More recent studies have shown that spatial abilities are malleable that can be learned and improved upon with training (Sorby, 2009; Terlecki et al., 2008).

The use of early spatial ability tests brought to light important issues. The first of which is the understanding that, spatial tests were designed to measure an individual's ability assuming a specific strategy and approach, and many students did not consistently employ any one strategy. Therefore, the "switching" of strategies complicated the interpretation of test results and the tests. The fact that subjects were solving spatial problems without using the ability the tests were designed to measure caused the results to be invalid (Harle & Towns, 2011; Ramadas, 2009). Additionally, these tests did not provide information on the use of different strategies (Harle & Towns, 2011). Early tests were primarily designed to measure mental rotation through the use of matching tasks, and the use of qualitative research methods helped researchers to realize that the same strategies were not being employed by all of test participants. Once researchers began to implement qualitative methods they were able to tease out some of the details of the different strategies, and describe when they were applied (Harle & Towns, 2011; Stieff 2010). Studies done by Bodner and Stieff mentioned later in this section, asked participants to use think-aloud strategies as they solved spatial tasks. These explanations provided evidence that participants were not using mental rotation, as assumed, to solve spatial tasks (Bodner & Guay, 1997; Stieff, 2010). As more was learned about spatial ability, more appropriate methods for measuring it were developed. Two major processing strategies are known to be used when solving spatial tasks: Gestalt processing and analytic processing (Bodner & Guay,

1997). Gestalt processing relates to the processing of “wholes”, and it is thought that this is the best cognitive measure of spatial ability because it requires an individual to rotate, form, or somehow transform a visual image as a complete entity. Analytic processing occurs when a spatial task is broken down into parts and systematically assessed. Sometimes, depending upon the level of difficulty of the problem, analytic processing involves “guess and check.” After reaching the conclusion that current tests “required only a minimal amount of gestalt processing and a significant amount of analytic processing” Bodner and Guay developed the Purdue Spatial Visualization Test for Rotations, PSVT:R (Bodner & Guay, 1997, p. 7).

The Purdue Spatial Visualization Test for Rotations was developed to address the concern that existing spatial tests were confounded by analytic techniques, and that the correct cognitive processing strategy was not being measured (Bodner & Guay, 1997). The PSVT: R was developed to maximize gestalt processing and minimize analytic processing and thus be a truer measure of spatial ability than existing tests. The development of this test allowed us to learn more about the types of cognitive processing being used, which has allowed for better understanding between spatial processing and other types of student learning.

The PSVT:R asks individuals to view an object within a box and compare it to an image shown below the box. The individual then selects the corner of the box that matches the represented image. To solve these kinds of questions, the viewer has to imagine what the object looks like from each angle and correctly match the 3D image. To minimize analytic processing there is a strict time limit of 30 sec per question. The authors of the test suggest that it could be used as a research instrument to measure

students' abilities to work with multiple representations, and to investigate alternative approaches to problem solving (Bodner & Guay, 1997). Thus, the PSVT:R has the potential to gain further information about student spatial ability. The test can be followed up with qualitative questions to obtain a sense of the thinking processes involved. It is worth mentioning that this test is still the most widely used measure of spatial ability, sixteen years after development (Harle & Towns, 2011). A couple of the current intervention strategies for improving spatial ability use the PSVT:R as a pre/post measure (Ferguson, 2008; Sorby, 2009).

D. Spatial Ability and Chemistry

Each of the 3 major factors identified by Lohman (1979) relates specifically to the field of chemistry, because students need to be able to visualize molecules in three dimensions to understand their structure and function. Some examples of general chemistry knowledge that apply spatial reasoning skills include: valence shell electron pair repulsion theory (VSEPR) to understand geometry, electron density distribution and polar molecules, kinetic molecular theory, crystal structure, and intermolecular forces. For students to understand and apply their general chemistry knowledge they must be able to integrate their spatial skills and conceptual knowledge (Ramadas, 2009). Students majoring in chemistry enter organic chemistry with the core content from general chemistry, and the concepts taught in organic chemistry continue to build on prior knowledge as well as develop a deeper understanding of why these concepts are important. Therefore, content areas, which apply spatial reasoning need to be developed in general chemistry so that students have the necessary background.

Organic chemistry asks students to *reason with* spatial information in order to understand chemical pathways and synthesis. This may be one reason why it is perceived as being challenging by many students. For the most part, students in general chemistry courses need only to understand spatial information related to simple valence shell electron pair repulsion (VSEPR) structures; the curriculum requires very little if any application of spatial knowledge. By contrast, in organic chemistry, identifying important spatial relationships is a primary aspect of the course. For example, students' need to discern differences between stereoisomers, understand the thermodynamic stability of different conformers, and differentiate between structural forms produced through reaction mechanisms.

1. Suggestions for Teaching

Various studies in the 80's and 90's showed mixed results with respect to strategies for improving spatial ability (Bodner, 1997; Harle & Towns, 2011). Practice with spatial tasks appeared to show improvement, but the length of time required for training had yet to be determined. Currently, research is aimed at methods to improve 3D skills, where previously the research focus has been to simply identify the differences between the different skills. In a general sense it has been suggested that the most effective technique for teaching students about spatial tasks is to make them clearly visible to the students, and diligently review these skills when they are required for interpretation (Harle & Towns, 2011). Teachers should explicitly teach how to interpret dash, wedge cues and demonstrate how they use them to reason between 2D and 3D representations (Harle & Towns, 2011; Ramadas, 2009; Wu & Shah, 2004). There is also evidence to suggest that having students sketch molecular shapes,

interactions, and particulate drawings helps them to make connections between the particulate level and the macroscopic level (Gabel & Sherwood, 1984). Teaching visuospatial¹ analytic techniques, such as symmetry planes, may help to reduce the cognitive load for students (Harle & Towns, 2011; Ramadas, 2009). Visualization tools, such as molecular modeling programs, have also been shown to be helpful to a large number of students of all ages to learn about the spatial properties of molecules (Coleman et al., 1998; Schwartz & Heiser, 2003; Stieff, 2007; Sorby, 2009; Terlecki, et al., 2008). As with many aspects of teaching it is emphasized that students require lots of practice with a variety of techniques to feel comfortable using them to solve problems.

E. Improving Spatial Ability

As mentioned earlier, it was believed for a period of time that spatial ability was an innate genetic ability, and therefore was not able to be improved upon with practice (Harle & Towns, 2011). However, more recent studies suggest that spatial ability can be improved upon with practice and focused interventions (Coleman & Gotch, 1998; Harle & Towns, 2011; Ramadas, 2009; Sorby, 2009, Terlecki, Newcombe & Little, 2008).

1. Spatial Training Studies

Studies by Terlecki, Newcombe and Little (2008) showed that continued training with molecular models and analytic techniques such as symmetry planes, helped to improve spatial ability, and that students were able to recall what they had

¹ These cognitive functions allow for the visual perception of objects and the spatial relationships among the objects.

learned and apply it. Importantly, the improvement was seen regardless of previous spatial experience, or gender, and appeared to be long lasting.

Sorby's study (2009) of 1st year engineering students, taking a course designed to improve 3D spatial skills, showed that students identified with weak spatial skills earned higher grades than those who did not take the course. Very important was that students who participated in the training course, especially women, were retained in engineering at a higher rate than previously observed, (although the study does not provide data for the previously observed comparison). In this study, it was found that easy surface development problems were generally solved with imagery techniques or "wholes" (gestalt), and analytic techniques were used for complex tasks, supporting Bodner and Guay's findings (1997). Further research found that high spatial ability students benefited from practicing tasks and receiving feedback, where low spatial ability subjects benefited most from training with visualization strategies (Sorby, 2009; Stieff, 2010; Taagerpera & Noori, 2000). Sorby's study showed that the growth trajectories for men and women with high spatial abilities appeared to level off during the 10-12 week instructional period. The low spatial ability women showed continued growth throughout the study and did not level off. However, it should be noted that this group had not yet reached the achievement level seen by the high ability groups, although it was very close (Sorby, 2009). This study provides some evidence that with appropriate guidance students can improve their spatial ability, which then in turn allows them to be more successful in their engineering studies.

In another intervention study with first year undergraduate engineering majors Ferguson (2008) used hand-held mechanical dissection manipulatives for the treatment

group. Both engineering groups, the control and the treatment group, were taught how to sketch, but the treatment group also had the manipulative to assist them. Ferguson found a statistically significant improvement in the pre/post scores of the Purdue Spatial Visualization Test (PSVT:R) following instruction. This improved performance was largely attributed to the sketching process related to the hand-held manipulative models used in that group. In this study, students with low previous experience had greater gains than students with experience, and STEM majors showed greater gains than the students who were not in STEM majors (Ferguson, 2008). This study is relevant to my study because it provides evidence that students without prior experience respond to basic training that allows them to be more successful with in the STEM disciplines.

2. Reasoning with Spatial Information

When studying the learning of spatial information it is important to consider that students may not be able abstract the information we expect (Schwartz & Heiser, 2004). Students need to be provided with opportunities that allow them to construct their own meaning of spatial representations (Gardner, 1993). Gardner was one of the first to actually identify spatial ability as a specific form of intelligence. He recognized the need to focus this important skill on when supporting a variety of student learning modalities. Piaget (1969) lists mental imagery, which directly relates to a students ability to visualize in 3D, as one of the later symbolic functioning types to appear developmentally in the operational stage. The extent to which it is developed by a given age depends upon the student's environment and learning opportunities.

It is believed that spatial representations interact with other forms of knowledge, such as visual and descriptive knowledge (Schwartz & Heiser, 2003; Wu & Shah, 2004; Kozma, 2006; Steiff et al., 2005) and therefore, students benefit more when they have the skills to separate a task into component parts. As with many forms of instruction deliberately focusing on a stepwise progression may aid in moving the students from novices to experts, as supported by research discussed below. Schwartz and Heiser (2003) suggest that imagery is relatively “effortless” for learners to construct, as long as appropriate structural cues are used. This may apply to visual-spatial tasks associated with molecular structures used in chemistry. The integration of imagery and the motor system can help students solve 3D problems, such as mentally rotating molecular images (Ramadas, 2009; Schwartz & Heiser, 2003). It is also thought that this integration allows for better anticipation of possible changes in molecular structure. As mentioned previously, results of studies with visual rotation tests, such as the PSVT:R support such suggestions (Bodner & Guay, 1997). Specifically, the data collected by Sheppard and Metzler (1971), showed that a linear relationship existed between the angle of rotation and the time it took participants to identify and match a rotated object. This finding suggests that participants used imagery to mimic the task as though they were actually performing it.

3. Expert/Novice Distinctions

When considering how to assist students in the acquisition of spatial skills, an understanding of how to move them from novices to experts is informative, because many professors have acquired expert status within their field, but perhaps not expert teaching status. Instruction should provide “the experiential basis for complex and

gradual processes of conceptual change” (Smith, diSessa, Roschelle, 1994, p. 154). Their research suggests that the reason novices may be more concrete thinkers is largely due to experience and assessment. They found that when novices were provided with appropriate tasks that allowed them to discover and formulate relevant questions, they used more abstract thinking, which may serve to anchor future learning on the way to becoming more expert-like (Smith et al., 1994). This may likely be the case with students’ spatial reasoning skills, as some recent intervention studies have shown (Sorby, 2009; Terlecki et al. 2008) that experiences provided through training allow for the development of expert-like skills. Through instruction and practice students involved in these studies adopted heuristic strategies, which were considered to be more advanced, because they were similar to strategies employed by experts.

4. Learning Chirality and Isomerism

A recent study by Taagepera and Arsasingham (2011) assessed the impact of laboratory exercises using a plane of symmetry in conjunction with molecular modeling kits. The study was designed to assist introductory organic chemistry students with their learning about chirality² and isomerism³. Participants in this study were primarily biology majors who had successfully completed a year of general chemistry. During the study students manipulated molecular models and identified planes of symmetry. They also learned how to recognize super-imposable mirror images. Students were given a pre/post test to assess their knowledge of chiral molecules and isomers, which was analyzed for correct responses. The connectivity of their responses were assessed using

² A molecule exhibiting chiral properties. A molecule that has a non-superimposable mirror image.

³ Molecules that have the same molecular formula but different structural formulas.

the Knowledge Space Theory (KST), which is a method developed for mapping the cognitive process of the students. The KST uses student responses to questions that reflect different levels of understanding, for the concepts of interest, in this case chiral molecules and isomers, these responses for each student are called response states. Based on all possible student response states the KST recognizes a subset, called the knowledge structure, which is determined by the most common response patterns. The KST allowed for the identification of the most probable learning pathway (critical learning pathway) for this group of students. The pathway allows for some analysis of student responses, relative to the learning pathway identified. This methodology can check for true comprehension and logical progression versus simply selecting the correct answer. Experts also take the test, so that their learning pathways can be mapped against the students, gaining information about how to best articulate expert reasoning to students, and this information may be helpful to professors in making their own thinking transparent to their students. The analysis of the KST data found that identifying symmetry planes came late in the students' knowledge structure sequence, as compared to experts. Importantly, even the treatment groups that had practiced examining planes of symmetry with molecular model kits, had symmetry plane identification late in their knowledge structures. Taagepera and Arsasingham (2011) stressed that the analysis of a symmetry plane through a simple molecule is important for conceptualizing and visualizing the presence of a symmetry plane in a more complex molecule. This is an important point. Often not enough attention is paid to the significance of the relationships between simple and more complex structures that may be useful in building a learning progression. For example, I have found that teachers

skim through the simple molecular structures and then have to spend more time with the complex structures, because they don't take the necessary time to clearly develop connections between the simple and complex structures. The overall, significance of Taagepera and Arsasingham's (2011) study was the result that the acquisition of the skills needed to find a plane of symmetry came later than expected in the students' knowledge structures when assessed with KST. The results of their study suggest that the use of symmetry planes to simplify spatial features of molecules may not be as helpful for many students as previously thought in other studies (Wu & Shah, 2004). Several studies have considered the use of symmetry planes as an analytic strategy that simplifies the spatial information for students and reduces the cognitive load (Ramadas, 2009; Stieff, 2010; Terlecki, et al., 2008). Based on the findings above the use of symmetry planes to facilitate the understanding of chiral molecules and isomers likely requires more practice for students to use it effectively.

F. Cognition and Spatial Reasoning in Chemistry

To work with spatial information in molecular structures and related chemical pathways we rely on cognitive processes that allow us to perceive three-dimensional information such as imagining and visualizing, once familiarity is gained, common features might be recognized. Students need to be able to conceptualize, judge and reason with this spatial information. Some thoughts about how they might go about doing this are included below.

1. Organizing Principles

The Structure-Behavior-Function (SBF) theory developed by Hmelo-Silver and Pfeffer (2004) lends itself well to learning chemistry in the sense that when teaching

about molecules many chemistry teachers, explicitly teach the idea that “structure dictates function.” When trying to understand and interpret complex systems “a person constructs a network of concepts and principles about some domain that represents key phenomena and interrelationships” (Hmelo-Silver et al., 2003, p.276). Using the Structure, Behavior and Function (SBF) network, it was revealed that novices varied from experts in the extent and type of networks used to problem solve. For novices, it was shown that structures were the most “cognitively available” level of complex systems, while experts mentioned mainly functional aspects (Hmelo-Silver et al., 2003, p. 136). Implications for teaching and learning were revealed through the understanding that the functional aspects mentioned by the experts, required more elaborate networks relating functional aspects to structure and behavior elements. Novices tend to represent the most perceptually available structure the best (Hmelo-Silver et al., 2003), because they have not yet built up stores of mental representations and associations to draw from to allow them to make these elaborate connections. In chemistry, much of what the learners are learning about is not available for direct perception and instead they rely on model construction to help make sense of intangible phenomena. Chemists utilize physical molecular models, computer images and computer simulations to help represent and bring meaning to small particles and their interactions, and these help them to reason with complex spatial properties. This study lends insight into the process for novices learning to reasoning with spatial information, on their way to becoming more expert-like.

2. Brain-sight

Brain research has shown that people can form clear and accurate mental images without the aid of visual perception (Wesson, 2012). In fact, the mental image formed is often more accurate when not made by visual observation, but by tactile sensory information. Often multimodal learning opportunities where students learn through observation, touch, and listening allow them to gain the deepest understanding. “When shapes are meaningless we form incomplete perceptions of them” (Wesson, 2012, pg. 5). This supports using molecular models to situate information in a more meaningful way by creating connections that allow for better recall. Wesson’s article about “brain-sight” also mentions that the sense of touch is processed in the somatosensory cortex which is directly connected to the lateral occipital cortex where sight is processed, suggesting that this close link allows for augmented communication within those regions of the brain (Wesson, 2012). This understanding also suggests that the use of a manipulative, such as molecular models, would enhance spatial perception through touch, helping students achieve a deeper understanding for the spatial properties of molecules.

3. The Information Processing Model

The Information Processing Model, which compares the human mind to a computer, resulted in understanding of early cognitive processes. The strength of this model lies in the simplicity and the organization of different memory stores. While this model does not explain much about how the cognitive processes actually work, it provides a useful framework for thinking about how encoding in working memory (WM) may be linked to long term memory (LTM) storage and retrieval processes. One version of this model is shown in Figure 1. In this model external phenomena are

perceived and brought into the working memory to be decoded, and/or encoded, sometimes eliciting a response. It is speculated that information that enters the working memory may be stored in the long-term memory in a variety of ways, some of which include rehearsal, and connections to other items already existing in the long-term memory. A central aspect of this theory is that information is “processed” and not simply reacted to as proposed in the stimulus response theory held by behaviorists. A key factor in this processing is the working memory, which is reported to hold between 4 and 7 items of information at any one time (Eysenck & Keane, 2010). In order to maintain things in working memory they need to be rehearsed or encoded in some manner, otherwise items are rapidly replaced with new information. The application of both visual and tactile modalities in this research allows for multiple encoding opportunities, which may lead to better retention and connections to long-term memory.

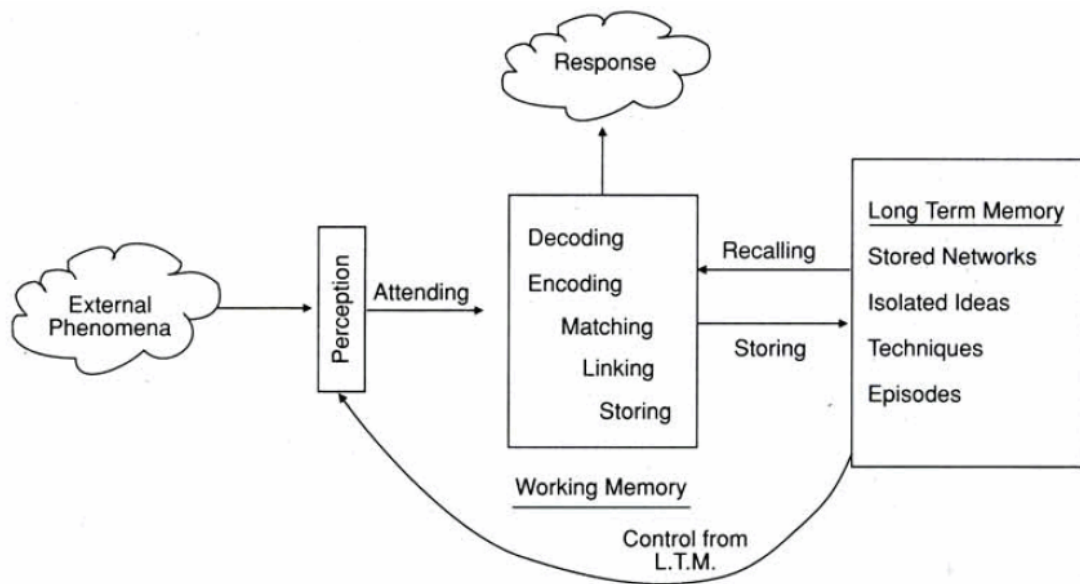


Figure 2.1 Information Processing Model (one version)

4. Spatial Working Memory

One popular model of working memory as described by Baddeley and Hitch (1974) and Baddeley (1986) proposes that there are four component parts. The first being, the central executive area that connects to three other specific areas, the phonological loop, the episodic buffer, and the visuo-spatial sketchpad, all of which bring information in to the central executive area in WM. The area of interest for my study is the visuo-spatial sketchpad, which is involved in the temporary storage and manipulation of visual patterns and spatial movement. This model suggests a single system that combines visual and spatial processing (Eysenck & Keane, 2010).

Recently, it was proposed that the visuo-spatial sketchpad consists of two areas, the visual cache and the inner scribe (Logie & van der Meulen, 2009). The visual cache stores information about visual form and color, while the inner scribe is responsible for processing spatial movement (Eysenck & Keane, 2010). The inner scribe also rehearses information from the visual cache or central executive processing area of working memory (Eysenck & Keane, 2010). Understanding the areas of working memory and how they process visuo-spatial information may aid in understanding how to assist students with the processing and storage of spatial information.

G. Johnstone's model of Chemistry Learning

In the chemical education literature (Gabel, 1998; Harle & Towns, 2011; Herron, 1999) one of the primary (if not the primary) influences early on has been the work of *Alan H. Johnstone* (2000; emphasis added). His perspective was that “we take too much care with the chemical content part and not enough attention is paid to the educational part of student learning.” (p. 34) He felt this evolved historically out of respect for the

discipline. However, he strongly urged that we take a look at human learning patterns and see if they are compatible with the adult “expert” conception of chemistry. Johnstone proposed a model (see Figure 2) that has since been cited regularly in chemistry education literature, and has guided chemistry teaching for a little over two decades (Gabel, 1998; Herron, 1999; Ramadas, 2009). In his model Johnstone stresses three important areas of chemistry instruction: macro-chemistry or macro (the tangible, edible, and visible), submicro (molecular, atomic and kinetic), and the representational chemistry (symbols, equations, stoichiometry and mathematics).

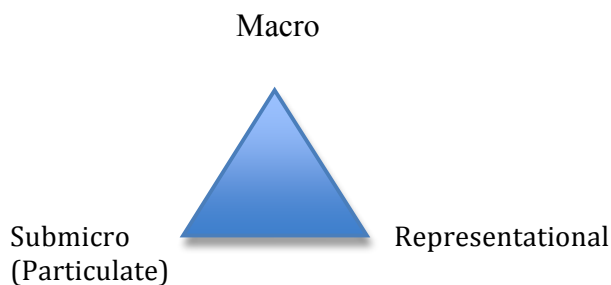


Figure 2.2 Johnstone’s Levels of Chemistry Knowledge

Johnstone argues that much useful chemistry could be taught at the macro corner of the triangle, thus making chemistry more tangible and meaningful. Johnstone also recognized that expecting novice students to reason within this triangle was asking far too much of them cognitively because they had to attend to far too much information at one time. Johnstone employed the information-processing model to understand why students experienced difficulty with meaningful understanding and recall of factual information. (See Figure 1). He believed that when students are attending to too much information they have a very difficult time differentiating between what is important and what is not.

Their working memories become overloaded, and as a result they often experience frustration (Johnstone, 2000).

As educators we know that what students perceive from phenomena is significantly impacted by their life experiences, which are believed to be situated in their long term memory (LTM) in the form of episodes, emotional events, techniques, isolated ideas, and stored networks. Constructivist learning theories place emphasis on understanding students' prior knowledge, and encourage educators to use methodologies which make connections to students prior knowledge while at the same time drawing out alternative conceptions (Brooks & Brooks, 1999). What students think is important, and interesting is influenced by what they already know, making associations to prior knowledge allows students to store information in their LTM networks in such a way that it is more easily retrieved. Strengthening spatial reasoning ability requires students to build the necessary memory associations that will allow them to use spatial information appropriately. How students build the necessary associations and more generally, process spatial information as it relates to chemistry requires further study. The information processing model employed by Johnstone has been replaced by more current representations of working memory (Baddeley & Hitch, 1986; Logie & van der Meulen, 2009) that seek to understand how the information is processed in working memory. Knowledge of these cognitive models informs my research as it seeks to understand how students' acquire spatial skills. Further, these models may be useful in understanding how students apply their knowledge of spatial information to solve spatial problems.

H. Developing Spatial Skills in Chemistry

The area of spatial reasoning in science has been the topic of much research (Gilbert, 2005; Mohler, 2008; Ramadas, 2009; Schwartz & Heiser, 2003; Sorby, 2009; Stieff, 2010; Wu & Shah, 2004) and along with this research have come suggestions for teaching methodologies, which support the improvement of spatial visualization and spatial reasoning development. However, there have been few studies carried out to substantiate any particular approach. Studies are calling for research in this area (Harle & Towns, 2011; Ramadas, 2009; Uttal, 2012; Wai, 2009). Additionally, thus far, only a few research studies have been focused on student performance in chemistry (Stieff, 2007; Sorby, 2009; Taagerpera & Arrasingham, 2011; Terlecki, et al., 2008) and an approach to spatial skill training has yet to be suggested for general chemistry. My research focuses on improving general chemistry students' spatial skills through the implementation of guided activities and gathers mixed data to analyze their effectiveness.

In addition to the literature mentioned earlier in the section *spatial ability is malleable*, several studies influenced the development of the intervention activities. These studies confirmed my pilot study findings (Carlisle, 2012) and helped to further support my goals in this study. First, as previously mentioned, research by Taagerpera and Arasingham (2011), underscored the importance of integrating an understanding of symmetry and symmetry planes for students in introductory organic chemistry, showing that students found it difficult to locate symmetry planes on simple organic molecules. Understanding that finding a plane of symmetry came late in students' knowledge structures (Taagerpera & Arasingham, 2011) was influential in my decision to spend more time on symmetry plane analysis in my intervention activities.

Secondly, partially due to Ferguson and colleagues' (2008) results and to those of Terlecki et al, (2008) where of the importance of using a manipulative to assist students with sketching was shown, I integrated molecular models as a tool to assist the development of students' representational skills in my intervention activities.

Finally, Kozma and Russel (2006) emphasized the need for chemistry students to be trained in representation, so that they could accurately sketch molecular structures. They made the case that "representational competence" was a critical step in students becoming chemists (Kozma & Russel, 2006, p. 121), based on their findings that student sketches were often incorrect, adversely affecting their problem solving strategies. My pilot study found that chemistry majors had little training in the art of representation and that their understanding of sketching stemmed mainly from copying sketches made by the professor. Kozma and Russel's research (2006) supported my pilot study results and underscore that this skill was tied directly to students ability to visualize. These findings supported my decision to have students focus on their representational skills in all of the intervention activities.

1. Influential Learning Theories

a. Constructivism

Constructivism provides the overarching principles for this research. Constructivist teaching practices "help learners to internalize and reshape, or transform, new information" (Brooks & Brooks, 1999, p. 15) which leads to a meaningful form of learning that is likely to be recalled and transferred to new situations. Specifically, several basic tenants guide the view-point through which spatial skill acquisition is developed in my research. Understanding that students construct their knowledge based

on experiential opportunities shaped the focus of the intervention to provide students with meaningful hands-on activities from which to construct their own knowledge. Spatial skills can be abstract and an important step in designing the activities was to distill the meaningful “big ideas” and connect them to relevant chemistry content. As constructivist theories suggest, students need to see the whole before they can appreciate the parts, and structuring learning around broad concepts allows multiple entry points for students to become engaged (Brooks & Brooks, 1999). Spatial reasoning was presented through activities that encouraged students to analyze, compare, and contrast molecular structures, rather than as a set of helpful facts that would allow students to consider spatial features of molecules. The activities were also set up to guide students such that they would discover the relevance of these skills as they worked to answer the guiding questions, thus as constructivist theories show students need not have pre-existing interest. Teachings themselves can create interest and stipulate the types of learning students pursue, as noted by Bruner (1971). Importantly, constructivist theories acknowledge relativity, by seeking to understand students’ point of view. Constructivism specifically recognizes the importance of allowing student’s to express their point of view and acknowledges that this is important in developing student understanding, not simply the “right” or “wrong” answer (Brooks & Brooks, 1999). Intervention activities are designed so that students need to explain their perspective to one another, while they problem solve and construct knowledge. As Bruner (1971) states “A method of instruction should have the objective of leading the child to discover for himself (p. 123)”. Finally, to truly interpret student learning and understanding constructivist theories recognize that real problems rarely have one right answer, for this reason student learning

should be assessed within the context of the learning process itself. Piaget's foundational theories note that there is rarely one correct "answer" to a meaningful problem. These principles guided the researchers development of activities as well as her observational process.

b. The Models and Modeling Paradigm

This paradigm developed by Lesh, Hoover, Hole, Kelly and Post (2000) and Case, Okamoto, Stephanson, and Bleiker (1996) is useful to gain understanding of how students think, because it provides understanding of their mental activities through the observation of thought revealing activities (Bodner & Orgill, 2007). This paradigm complements constructivism by providing an understanding of the mechanisms through which students construct their knowledge. In this paradigm the methods and theory are closely related, and build off one another, because the theory provides a guide from which to develop "thought-revealing activities" (Bodner & Orgill, 2007, p. 73). Within the Models and Modeling paradigm the constituents are:

- 1) The referents, which can be physical or mental, symbols or equations, or a manipulative (Bodner & Orgill, 2007). In this study the molecular models are the referents.
- 2) The relationship between the referents, such as position or cause and effect (Bodner & Orgill, 2007). In this study it would be molecular orientation, and how molecules could interact with one another.
- 3) The rules or syntax that dictate relationships between the referents in order for them to have meaning (Bodner & Orgill, 2007). For example, bonding patterns between atoms in a molecule have to be correct adhering to specific rules.

4) The results allow for the derivation of new knowledge from an experience or mental manipulation (Bodner & Orgill, 2007). For a spatial activity this might be the understanding of the relationship between 2D dash and wedge notation and a 3D molecular model.

5) The operation acts upon the referents and is dynamic in nature (Bodner & Orgill, 2007). For a spatial activity this could be the result of a molecular rotation using molecular models.

These constituents allow a researcher to make observations of students operations and to use think aloud protocol to illuminate how students learn, thus providing a useful framework to elaborate on students knowledge construction.

c. Theoretical Framework for This Study

Integration of Constructivism, Models and Modeling, and Cognitive Psychology

This research is grounded in the theoretical frameworks of Constructivism developed and influenced by Dewey, Montessori, Vygotsky, and Bruner as described in *The Case for Constructivist Classrooms* by Brooks and Brooks, 1999, and is also influenced by the Models and Modeling Paradigm developed by Lesh and colleagues as outlined by Mike Briggs in *Theoretical Frameworks for Research in Chemistry/Science Education* by Boder and Orgill, 2007, as well as being informed by cognitive psychology. Constructivism is the primary influence on my current theory of learning; the Models and Modeling framework builds on constructivism by providing an understanding of the mechanism through which knowledge construction occurs, while cognitive psychology has improved my understanding of these mechanisms. The over-arching basic tenants of constructivism that influence this work are: 1) structuring learning around primary

concepts, 2) posing problems of emerging relevance, 3) seeking and valuing students point of view, 4) adapting curriculum to address students suppositions, 5) assessing student learning in context (during active engagement with content) (Brooks & Brooks, 1999). These constructivist tenants are the foundation for understanding spatial skill development and for the development of my intervention activities. First, skill development was grounded in concepts that tied to what the students were learning about. During the development of the intervention activities the need to know information was distilled, and connected to the big ideas. Guiding questions with spatial information were developed to be engaging to students, and were designed in such a way as to become more interesting for students as they worked through the tasks. Recognizing that students may not realize the value of spatial information, the activities will allow them to develop an appreciation for these important concepts by actively working with spatial activities. Students will share their thinking verbally and through their representations, while performing thought revealing activities, whose development was guided by the Models and Modeling framework. Gathering data as students share their ideas and drawings will allow for an authentic observation of student understanding in the context of the learning process. Problem solving will include group discussions encouraging students to seek and value each other's points of view, their descriptions and external representations will clarify their internal thinking, which will help in clarifying their understanding. In this way the tenants of constructivist learning theories were a guide both theoretically and methodologically. Theoretically they provided a lens from which to view student understanding, and methodologically they guided the creation of meaningful activities.

To use the models and modeling framework effectively, I applied my understanding of cognitive psychology as it relates to student ability when reasoning with spatial information. Cognitive psychology is engaged with the understanding of learning processes; it explains the brain functions involved as information is perceived and encoded (Eysenek & Keane, 2010). My research focused on gathering data to understand how students learn spatial skills while engaged with the intervention activities. Cognitive psychology offers explanations for how the students' minds take in, process and act upon information associated with the spatial skill activities. For my research the relationship of the visual-spatial sketch-pad, working memory and long-term memory are important cognitive areas, because they offer explanations about how the visuospatial working memory (VSWM) processes spatial information from visual and perceptual input. Two important ideas emerged from the cognitive psychology literature, (1) one's ability to visualize aids in how they focus their perception (Chein & Schneider, 2012) and (2) understanding that stored information from long-term memory stores may be more important to the visuospatial area than the visual information from perception (Logie & Della Salla, 2005). These ideas were used to support both theory and methodology, because the intervention activities were designed to strengthen students' ability to visualize thus, focusing their perception on important molecular features as well as building LTM stores of common molecular structures, which in turn strengthens their ability to mentally reason with spatial information.

This framework, as well as the literature presented above, serve as a guide to the development of the spatial activities implemented in this study. They also act as a lens for the evaluation of these intervention activities. This literature review and theoretical frame

will provide a solid foundation that will be used to answer my research question. Data gathering as well as data analysis are informed through this framework.

CHAPTER III

METHODS

A. Introduction

The ultimate goal of this research is to assist undergraduate chemistry students in the development of their spatial reasoning skills, allowing for a broader range of students to acquire these important skills and prepare them for advanced chemistry course work. To accomplish this, an intervention was carried out using molecular models to allow students to 1) sketch, 2) visualize, 3) translate and 4) explore molecular interactions. Additionally, this study seeks to gather data about how to best support student learning of these important skills, so that the spatial aspects of chemistry becomes more accessible. Descriptive qualitative data gathered during this study will be used to inform instruction for teaching spatial reasoning skills, including how to make them meaningful in large lecture setting.

This research has the potential 1) to further the understanding of how students acquire spatial reasoning skills in general chemistry, 2) to use this group of chemistry students as a base-line reference for understanding what facets of spatial reasoning other groups of chemistry students may find useful, and 3) to suggest teaching strategies to support spatial reasoning in general chemistry courses for high school and undergraduate students. Overall, this study will inform pedagogical practice in general chemistry, with the aim of improving a broader range of student understanding among a diverse group of learners.

B. Research Question

Based on the purposes of this study the following research question was appropriate: In what ways does a spatial intervention support students' learning of spatial reasoning skills?

As there have not been specific studies with in undergraduate science, and more specifically within the discipline of chemistry, which describe successful approaches to student learning of spatial skills, this question allows for a broad exploration of the ways in which the intervention activities supported student skill acquisition. Qualitative data will provide authentic descriptions of the ways in which the intervention helps students to acquire spatial reasoning skills. The research question also allows the researcher to employ quantitative data collection methods that will illuminate how well students are able to transfer their understandings.

C. Problem Statement

For the vast majority of students spatial ability is learned and developed through life experiences (Harle & Towns; 2011, Wai, 2009). Often the details of spatial properties are not explicitly taught to students, and therefore students' interpretation of important conceptual information is based on their own assumptions leading to misconceptions or incomplete understanding (Carlisle, 2012). Based on my idiosyncratic knowledge it appears that spatial information is often implied, because it is embedded in abstract content that is complex, but oversimplified for a variety of reasons. The first, being the rapid pace at which a large amount of conceptual material is covered. Secondly, that spatial concepts are not adequately recognized to require teaching, because it is assumed students "pick it up" the necessary information by observing or visualizing. The

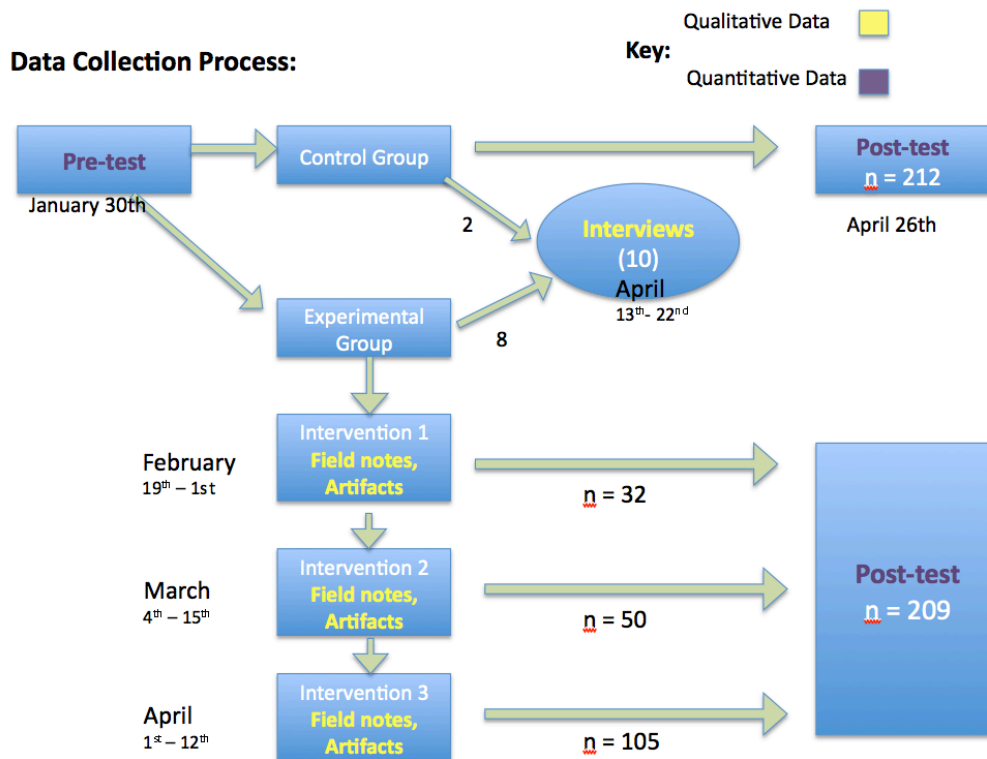
acquisition and development of spatial reasoning skills requires explicit teaching, this will allow all students a much better opportunity to learn (Sorby, 2009). Improvement of spatial understanding will allow a larger percentage of students to be successful in STEM disciplines (Wai, 2009). It is recognized that the small percentage of students who have special talent, life experiences, or prior knowledge, which predisposes them to consider spatial information, have a significant advantage when it comes to making connections and recognizing the deeper significance of conceptual information (Uttal & Cohen, 2012, Wu & Shah, 2004). It is also possible that improved learning of spatial reasoning will lead to a broader conceptual understanding, which may allow for more creative and innovative thinking within the discipline (Ramadas, 2009).

Many disciplines including engineering, physics, mathematics, molecular biology, chemistry, or architecture require students to have the ability to reason with spatial information. In fact, student success in virtually all of the STEM disciplines is influenced by spatial ability (Davidowitz & Rollnick, 2011; Sorby, 2009; Wai, 2009; Stieff, 2007). It seems that students who don't receive explicit training or practice with spatial reasoning are disadvantaged in successfully completing advanced science course work and as a result may be more likely to drop out of STEM fields (NSB, 2010; Wai, 2009; Uttal & Cohen). Considering the continuing increase of jobs within STEM disciplines, it seems important to provide all students with opportunities to access these; developing and increasing their spatial ability is one important step towards this goal.

D. Research Design

This study was designed to gather data on the effectiveness of a spatial intervention developed by the researcher. To address the research question a convergent

parallel mixed method approach (Tashakkori & Teddie, 1998; Creswell & Plano Clark, 2011), was chosen for this study, because it allowed the researcher “to obtain different but complementary data on the same topic,” allowing for the research question to be more thoroughly explored (Creswell & Plano Clark, p.77). The quantitative part of this study used a post-test only control group design (Gall, Gall & Borg, 2008) as this is considered to be one of the simplest methods for testing the effectiveness of an intervention. The two groups did not undergo random assignment, however were selected to be as similar as possible, and are considered equivalent for the purposes of educational research, where researchers often assign similar classes and schools as a “group” because it is not practical or possible to achieve true random assignment (Gall, Gall & Borg, 2008; Urdan, 2010). A pre-test was used to establish homogeneity between the experimental and control groups prior to carrying out the intervention activities. In order to test whether or not the intervention (independent variable) had an effect on student performance (dependent variable), I designed a post-test that measured student overall performance for the quantitative strand of this design. The qualitative strand includes: field notes taken during the intervention activities in small groups, student interviews, and artifacts of student work, each of which contributed to an authentic description of the students experience with the intervention activities. Both of these strands were collected independently of each other. An overview of the design and the data collection process is outlined in Figure 3.1.



Note: The arrows in this figure represent the timeline of the study and not a causal relationship between each connection.

Figure 3.1 Data Collection Sources and Dates

1. Participants and Setting

The participants in this study were undergraduate students who were enrolled in the second semester of a two-semester general chemistry course (lecture and laboratory sections) for STEM majors. Two large lecture sections containing approximately 300 students each were selected for this study, and both sections were taught by the same male professor with 6 years of teaching experience. This population of students was selected, because organic chemistry would be the next chemistry course in their sequence, and these intervention activities were designed to help prepare them for their future chemistry course work. Given that undergraduates are often educated in large

lecture sections this intervention chose to consider ways to improve spatial reasoning skills within this realistic context.

The site of this study was large public research university in the Northeast of the U.S. The course was taught in a large lecture hall, in a new science building, that was well equipped with a projection system, laboratory bench and ample blackboard space.

After introducing the study to all students, students who were willing to participate filled out an informed consent form, which had been approved by the university's institutional review board, prior to conducting the study. The form indicated 1) that students would be engaging in spatial activities, 2) that students were not required to participate, 3) if they did participate they were free to withdraw at any time without penalty. Students did not receive credit for the intervention activities and participated on a volunteer basis.

The numbers of students participating in the intervention activities and in the post-test are given in Table 3.1. While the control group contained roughly even numbers of males (95) and females (110), the experimental group contained about twice as many females (138) as male (65) students.

Table 3.1 Participant Numbers

Scores	N
Experimental	209
Intervention 1	32
Intervention 2	49
Intervention 3	105
Control	212

**Note 6 students in the experimental group did not report their gender information, and 16 chose to not participate.*

2. Quantitative Instruments

Pre-Test and Post-Test

Both the pre- and post-test were 20 minutes long and the same test was administered to both sections on the same day with the experimental group receiving it first. Both tests were announced one week prior to administration. Each test was comprised of 21 multiple choice questions, which were projected in Power Point on large screens at the front of the lecture hall, and students responded to the questions via their own individual audience response devices (clickers). Each of the test questions was presented for 45 seconds. Students were not allowed to discuss their answers during the tests, and were not observed doing so. The responses were transferred from the audience response system software to Microsoft Excel for analysis.

The pre-test contained a total of 21 questions, seven questions were from the Purdue Spatial Visualization Test, PSVT developed by Bodner and Guay (1997) to test students' ability to rotate figures as wholes or Gestalts, which is thought to be the best cognitive measure of spatial ability, because it is the least influenced by analytic techniques. An example of such a question is shown in Figure 3.2.

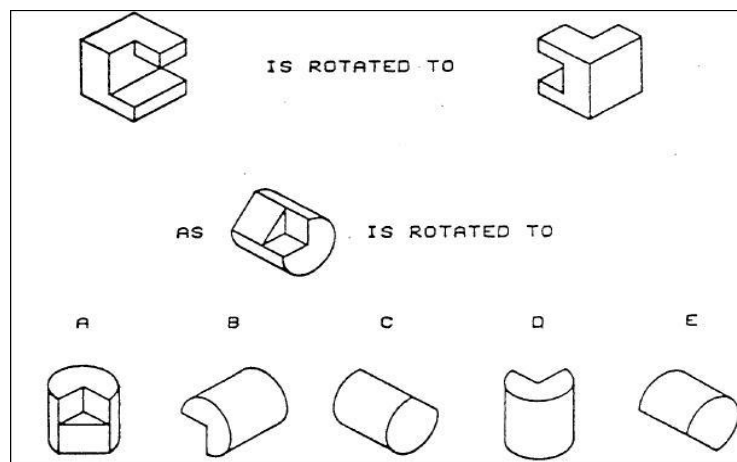
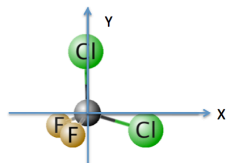


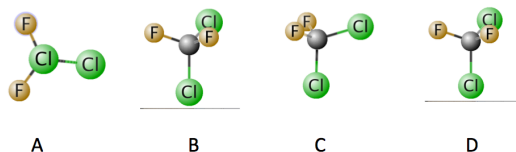
Figure 3.2 Example of Purdue Spatial Visualization Test

Although several studies have used the PSVT as a pre/post measure for spatial understanding, in this study 80 to 90 percent of the students in both groups correctly answered these questions on the pre-test. This led the researcher to develop further discipline specific test questions for the post-test to measure the skill acquisition of students in the experimental group, as she felt the PSVT would not capture the improvements, given the high scores earned by both groups initially. Thus there were no PSVT questions included on the post-test. In addition to the seven PSVT questions, 15 relevant content questions were developed specifically for this study. These questions address the areas of molecular geometry based on Valence Shell Electron Pair Repulsion (VSEPR) Theory, intermolecular forces, identifying similar molecules, interpretation of the dash/wedge convention, and the identification of a symmetry plane. These areas were selected, because they made relevant connections to spatial content within the course. Some questions required students to imagine molecular interactions in three dimensions given only a chemical formula, while others provided pictures of 3D molecular models. Examples of questions are shown in Figure 3.3. See Appendix A for the complete list of pre-test questions. The pretest was used to assess the homogeneity of the experimental and control groups with respect to spatial reasoning ability, and establish an understanding of both groups initial understanding of spatial concepts. I also developed the post-test specifically for this study, because discipline specific measures are currently not available that assess general chemistry students' spatial reasoning skills. The post-test contained a total of 21 questions; of these 15 were spatial questions, whose content was similar to those of the pre-test. Of the other six

12.



Which picture best represents what this molecule would look like after being rotated 180° on the X - axis?



15. VSEPR Theory

Which of these molecules, if any, is not flat?

- a) BF_3 b) PH_3 c) HCN
 d) O_3 e) H_2S

Figure 3.3 Examples of Pre-test Content Questions

questions, three asked about demographic data including questions related to the number of interventions performed and gender, while the other three were Likert-type questions that asked about spatial understanding. See Appendix B for the complete list of post-test questions. The test items were reviewed independently by two chemistry professors for content validity. These questions were found to be appropriate and relevant to current subject matter covered in the course. Suggested revisions to questions included clarifying solution choices, and simplifying choices for timing purposes; these were discussed and changes made accordingly. The post-test was used to compare the performance of the experimental group to the control group, who did not receive the intervention activities, for the purpose of assessing the effectiveness of the intervention (Gall, 2003).

Construct validity was established by tying the questions to cognitive factors for spatial reasoning skills based on theory proposed by Lohman (1979), while recognizing that spatial ability is a comprehensive construct. The cognitive factors represent the three major factors generally accepted as common attributes for spatial ability, spatial relations (SR), spatial orientation (SO), and visualization (VZ). Questions related to the construct of spatial ability were developed through a pilot study, and scoring showed significant

differences for these items. An analysis of the test is provided in Appendix C. The internal consistency and reliability of the post-test is given by the reliability coefficient, Cronbach's alpha $\alpha = .65$.

3. Qualitative Methods

a. Field Notes

Field notes were written during the small group intervention sessions carried out in the laboratory, with the researcher being both a participant and an observer (Merriam, 2010, Rossman & Rallis, 2012). Field notes were considered an important data source, because they provide a firsthand representation of student experience while engaged in the spatial activities. Field notes were recorded via short hand during the observations, capturing as much detail as possible; for example, they included direct quotes from students, as well as observer comments (OC) relating to the recorded observations (Merriam, 2010). Notes were then expanded and full detail added at the end of each intervention session. The researcher listened to and carefully documented student discussions during each of the intervention activities, focusing on details that she felt were relevant to spatial skill acquisition. How students interact with the activity and with one another? What appears to make sense? What does not? What aspects of the activities appear to be engaging? In what areas do students appear to struggle? These notes allowed for a general sense of student approach, common questions, and general interactions with the molecular models to be obtained within the context of the activity. Importantly, these notes (1) provided a record of student comments during each successive activity as they interacted in their groups, and (2) allowed a window into individual student thinking as they sketched, questioned, and made comments to a partner and occasionally directly to

the researcher. Thus, field notes provided a record of student understanding collectively and on an individual basis, which allowed for patterns to be identified across different groups performing the same activity. Careful observations allowed for clues and evidence leading to skill development to be identified as well as differences in understanding across successive activities. See Appendix J for representative quotes and comments grouped by theme.

b. Interviews

Interviews were conducted to probe student thinking in more depth, while they performed spatial activities. All interviews were tape-recorded using Garage Band and fully transcribed by the researcher. Interview questions were semi-structured to gain as much insight as possible into students' perspective while they reasoned with spatial information and performed tasks requiring spatial knowledge. However, the interview questions were flexible and fluid catering to individual students needs for processing the necessary information, and allowing the interviewer to probe more deeply, as needed, to draw out student thinking. The interview process was informed by Merriam's chapter "Conducting Effective Interviews" (2009), the researcher considered how to ask "good questions" and how to use interpretive questions as "a check on what you think you are understanding, as well as an opportunity for yet more information to be revealed." (p. 98) The interviewer was supportive, and nonjudgmental, yet careful not to provide information or lead students toward or away from a solution.

The interview questions were carefully drafted to tap students' spatial skills and to probe their understanding of the spatial concepts addressed in each of the three intervention activities, as such the questions asked were similar to those used during the

interventions. See Appendix G for interview questions. Eight students in the experimental group volunteered to be interviewed, and of the four who volunteered from the control group only two actually participated. All participants signed an informed consent form prior to participating in the interview process.

c. Artifacts

The researcher obtained copies of student work from all students following group sessions in the laboratory. Copies were made of student worksheets of the four laboratory sections, to allow for careful examination of student work. All student artifacts were reviewed and returned to students. Artifacts were examined for information that demonstrated student thinking and skill acquisition based on their recorded answers and sketches.

4. Procedure

Before classes began in the spring of 2013, both sections of General Chemistry were randomly assigned, through drawing, to the experimental group (n= 288) and to the control group (n=275). Both of these groups were chosen, because they were expected to have similar student enrollment and therefore allow for an accurate comparison.

Interventions

What is special about the intervention activities that I developed?

These activities strived to make molecules meaningful to students through the development of spatial skills that will assist their understanding of 3D molecular structure. The intervention focused on concrete spatial concepts, conceptual big ideas, and the need to know information linked to common molecules and familiar shapes, slowly building the level of abstraction. The activities provided students with unique and

necessary experiences. For example, making a sketch from a 3D molecular model was not something students had had experience with. Their course work requires them to copy sketches during lecture, or during homework from their textbook. Recognizing that skill acquisition requires practice, students repeatedly practiced interpreting 3D information from 2D sketches as well as representing 3D information from 3D models.

The interventions were short 15-20 minutes, learning to reason with spatial information easily leads to cognitive overload, and short activities did not over extend working memory (WM) capacity and lead to frustration. Cognitive research has shown that cognitive resources (WM and VSWM) are depleted when several challenging visuo-spatial tasks are required sequentially (Healey, 2011). The short time frame also helped students to stay focused and engaged. Importantly, models were made a central feature of the activities. My pilot study showed that some students appreciated the tactile aspect of molecular models. The haptic sensory area feeds into the visual cortex, making it very likely that this kinesthetic modality was improving their spatial understanding (Wesson, 2012). Because of this I incorporated guiding questions that required students to manipulate models. Cognitive psychology of spatial reasoning supports the notion that stored information in long term memory (LTM), can be accessed by VSWM (visuo-spatial working memory), and may be more important than visual information from perception (Logie & Della Salla, 2005). Therefore it is critical to have rehearsal activities that allow time for information to be encoded and stored in LTM, so that it can be retrieved in the first place. Lastly, research and my own teaching experience, has shown that students struggle with understanding the chemical formula, and the particulate nature of matter, which are core ingredients to general chemistry. The spatial knowledge

acquired during these activities increases the meaning and relevance of molecules and provides insight into the chemical formula through the visualization and imagination of 3D molecular structures (Gilbert, 2005; Johnstone, 2000).

The intervention activities were administered monthly during the students' laboratory periods for a total of three interventions over three months (February, March, and April). These activities had been developed and piloted with a group of chemistry majors ($n = 30$) in an organic chemistry course at the same university. Each intervention consisted of three activities, which required the use of molecular models to assist students with 3-D sketching, visual perspective taking, and translation between external representations (Hegarty, 2012; Sorby, 2009; Kozma, 2006; Gilbert, 2005). These three fundamental aspects of spatial reasoning were practiced in each of the interventions to allow for the reinforcement of developing skills. The researcher specifically designed these activities to connect the spatial reasoning skills to current content using the course syllabus. Units were selected that incorporated spatial reasoning principles, such as: intermolecular forces, or solutions and kinetics, which served to make the activities relevant to the students (Brook & Brooks, 1999).

The intervention activities were administered in the form of a worksheet with guiding questions that required students to:

- Interpret sketches incorporating dash/wedge cues
- View molecular models from different sight lines
- Sketch using dash/wedge notation from these different perspectives
- Compare and contrast molecular models in different orientations
- Locate symmetry planes

- Consider molecular interactions

Activities were carried out in self-selected groups of 2-4 students, and took 15-20 minutes to complete. Following brief initial instruction by the researcher, students carried out the activities independently, with the researcher present to answer questions and observe student participation. Students were at liberty to choose to participate in any or all intervention activities; this resulted in three groups based on the number of interventions conducted and allowed for information to be gathered on how many activities were necessary for students to improve their spatial skills.

The activities, summarized in Table 3.2, were designed by the researcher so that students needed to employ the several spatial reasoning strategies proposed by Stieff and colleagues (2012): spatial imagistic (a way of thinking that requires mental imagery), spatial diagrammatic (involves the construction of novel diagrams), and spatial analytic (requires the use of rules and heuristics) on spatial information to learn about and practice with the 3-dimensional features of common molecules. While answering questions, students shared their thinking and visualization processes with each other.

Templates and dot matrix paper were provided to support the sketching process (Sorby, 2009) by helping students to make their lines straight and to enhance the meaning of the dash/wedge. Activities were designed so that students shared their sketches with other students in their group. The researcher discussed and demonstrated ways to locate symmetry planes. For example, imagining an index card or a piece of paper slicing through the molecule in a particular location. This assisted students in decomposing a 3-D structure and facilitated their thinking about it in a 2-D perspective.

Table 3.2 Descriptions of Intervention Activities

Intervention	Content	Skills
1	Perspective taking, sketching a physical molecular model from different views using dash/wedge, identify/locate symmetry planes using a molecular model, relationship of symmetry to polarity, compare and contrast molecular shapes	<ol style="list-style-type: none"> 1. Visualizing from different perspectives, understanding view is relative. 2. Sketching- practice with representation and translation 3. Identifying symmetry planes 4. Note common features of molecules
2	Sketch from a physical molecular model using dash/wedge, identify symmetry planes, determine whether molecules are the same using <ol style="list-style-type: none"> 1) written 2-D sketches 2) physical molecular models 	<ol style="list-style-type: none"> 1. Sketching molecules 2. Translating spatial information from 3-D to 2-D, and visa versa 2. Identifying symmetry planes 3. Performing molecular rotations both mentally and physically
3	Position physical models to match 2-D sketch with dash/wedge, rotate molecular models around imaginary x, y axes, sketch physical molecular models incorporating dash/wedge, position models as though interacting, determine whether molecules are the same using <ol style="list-style-type: none"> 1) written 2-D sketches 2) physical molecular models 	<ol style="list-style-type: none"> 1. Visualizing molecular orientations and molecular interactions 2. Performing molecular rotations 3. Identifying similar molecules in 2-D and 3-D

E. Data Analysis

Data were analyzed using a convergent parallel mixed method approach (Tashakkori & Teddie, 1998; Creswell & Plano Clark, 2011), in which the qualitative strand and quantitative strands are given equal priority. This design allowed me to fully address my research question by using the description in my qualitative research to expand upon my quantitative findings. The post-test revealed areas where the experimental group scored higher than the control group and the qualitative data allowed

for student learning experiences in these areas to be analyzed. The convergent parallel design was originally developed for the purposes of triangulation, which was the identified purpose for using mixed methods in this study. As is characteristic of this methodology, the qualitative and quantitative data strands were collected independently of each other and the initial analysis of each strand was carried out independently. The data strands come together during the data interpretation stage, so that the findings can be directly compared and contrasted as needed for the purposes of corroboration and validation (Creswell & Plano Clark, 2011).

1. Quantitative Data Analysis

The data were prepared for analysis in Excel spreadsheets organized by student i-clicker number. Student responses to the multiple-choice questions were recorded and transferred directly from the student response-system to an excel spreadsheet. Using an answer key, correct responses for each question were assigned a value of one and incorrect responses were assigned a value of zero. Answers were either correct, or incorrect thus there were only two possible codes assigned. Within Excel each column was selected and the find and replace function was used to assign a one to each correct multiple-choice response (i.e. A = 1) all other responses were assigned a zero. Summarized scores for each student were obtained by assessing the number of one's in their responses to the 15 item test and a ratio (e.g. 13/15) was used to find the overall score for each student. Any missing data was removed from the group analysis. Statistical Package for the Social Sciences (SPSS) was used to analyze the data for the experimental and control groups.

The pre-test was administered to both groups before the start of the intervention activities, and an independent samples t-test for a normal distribution, with equal variances was used to establish homogeneity between the groups. Levene's test (F-test) was used to support homogeneity of variance with significance above 0.05.

The post-test data were collected to assess students' skill acquisition after engaging in the spatial activities, thus providing one measure of student learning. These data were analyzed with an independent samples t-test to compare the overall performance between the experimental group and the control group. A one-way analysis of variance, (ANOVA) was used to assess the performances of students participating in the different intervention activities. Students participated in either one, two or three, intervention activities or in no intervention activities (control group). The ANOVA is used to compare between group variance to within-group variance when there are more than two means. The value of the ANOVA is that it minimizes Type I error by decreasing the alpha value that is accepted as significant. A significant F value was found and a Tukey HSD test (honestly significant difference, post hoc) was run to determine which groups differed from each other significantly. These results allowed for an understanding of how many interventions resulted in the best performance. During this study, the quantitative data were collected to assess students' skill acquisition after engaging in the spatial activities, thus providing one measure of student learning.

The effect size was calculated using the Cohen's d value for 2 different analyses: (1) the overall experimental group and the control group, and (2) students participating in all three intervention activities and the control group.

The Cronbach's alpha reliability coefficient was calculated for the 15-item test as a measure of the test's internal consistency.

The researcher also analyzed the performance of the control group to the experimental group on individual items of the post-test to look for information about which skills showed the most improvement. Questions showing differences over 10%, were grouped by themes, for example identifying a symmetry plane. These themes were used as a guide to look at the individual interventions in which students gained experience with this concept. Questions showing the highest mean score for the experimental group were grouped and used as a focus to explore the qualitative data. The qualitative data was used to provide evidence of student engagement, practice, and understanding.

2. Qualitative Data Analysis

To gain insight into the students' experience and the ways in which the spatial intervention supported student learning, the qualitative data (interviews, field notes and artifacts) were used to provide a detailed description of student participation in the spatial activities. Through the lens of the theoretical frame these qualitative data were used to illuminate student thinking and to elaborate on the ways in which the activities led to spatial knowledge that required the use and development of spatial skills.

Field notes and interview data were coded for relevant findings relating to the research question. In a general sense, my coding process was informed by the works of Merriam (2009, p. 176) where one goes "back and forth between concrete bits of data and abstract concepts, between description and interpretation"; Strauss and Corbin's (1998) constant comparative methodology where one balances between inductive and deductive

reasoning; Coffey and Atkinson (1996) where coding is a way of “breaking the data up” so they can be opened and analyzed in new ways; and Rossman and Rallis (2012) who helped me with the organizational aspects of coding. A general overview of my process includes: open coding for words that are related to my research questions (identifying phenomena related to spatial understanding leading to related properties and dimensions to help describe); axial coding (linking properties and dimensions to categories, looking for patterns and collecting examples); and selective coding (deciding on central category and linking others to develop the “story” of the data through these identified relationships).

a. Analysis of Field Notes

During the data analysis the research question is written at the top of a blank coding page. The data is read and reread carefully thinking about the comments made by the students as well as my observer comments (Merriam, 2009). I noted thoughts and ideas in the margin of the field note page, which is double-spaced. Next, I generated a list of initial codes on my coding sheet based on patterns and initial ideas that I identified while reading through the data (Rossman and Rallis, 2012). Some of my early open codes were very simple; for example, “models help” (MH) was initially noted across all of my field notes, or “looks different” (LD), which referred to comments made by students with element of surprise, when they noticed the model looked different depending upon how they viewed it. An example of my coded field notes is shown in Figure 3.4.

Another says "can I draw NF3 from the top? I say yes - she sketches all F's w/dashes away (and she is right)

Another girl from other group has this ah hah moment and holds up PF5 and says "well it looks different depending upon how I hold it! If I look at side she sketches it, if I look at the top - she sketches... (interesting she was really enthusiastic about this - she seemed like she figured out something that had been alluding her). Pure evidence of thinking molecules as static!"

→ Clare 155E says to me (she was alone b/c her lab went late) for #3b - "Ok with models I really see it" "its hard to look at sketch and tell, but w/models if I can move them it's easy to see"

LD Element
MH

Figure 3.4. Open Coding Notes: Looks Different (LD) and Models Help (MH)

Data from the field notes were coded a second and third time to extend and clarify additional meaningful details, as well as to assess for similarities and differences. For example, after noting where models helped (MH) in the notes, I then looked more specifically at how they helped within these instances. One area where models helped (MH) was related to visualizing orientations through the process of molecular rotation. See Figure 3.5 for coded notes.

Grp 4
4 students (3 girls and 1 boy)

#1 they place the model like the sketch with lots of discussion about how this helps. Translation

F1 says "this really makes sense now that I can see it with a model" MH

F2 says "yes, the comparing really helps" - referring to 2D to 3D

M1 asks to hold the model (each group has two of the 2 butanol's) He takes it and rotates it around the y-axis as parts b) and c) say to do. F3 sitting next to him watches and then asks to hold the model and tries it too. They both say that it is the same no matter how you turn it, and look to the other 2 group members, who are currently making sketches. One asks "they are the same right?" (answer checking) MH

the other says "I think so" another says "Yes the same"

OC: They then decide to do the rotations again with everyone watching.

Second male student rotates to right and then back to the left. Others say "yes, definitely" and proceed to sketch. Rot

Models Assist w/Rot

Figure 3.5. Example of Axial Coded Notes for MH with Rotation

Looking more in depth at how the models were helping students to visualize molecular rotations led me to the realization that students were changing their answers on their

worksheet after using models in the second half of the question. I then went to the artifacts and tallied the number of students who did this.

Sometimes during data collection, I would be able to follow-up on a hunch or a question, collecting additional data with a second round of students, who carried out the same intervention later that day. This allowed me to efficiently follow-up on what I had seen with earlier groups. During the data analysis this helped me to make connections and to establish patterns more easily, if any existed. It also was a way to follow a thread of inductive reasoning and see how it compared to other instances relating to the same phenomena. For example, I noticed that some students did the rotations correctly with the molecular model, but needed the steps broken down to assist with an accurate sketch. I observed several student groups and made a note to check artifacts later. I made an observer comment that this may indicate students' need to have the steps for sketching broken down even while using the model. See Figure 3.6 for coded artifact of student work.

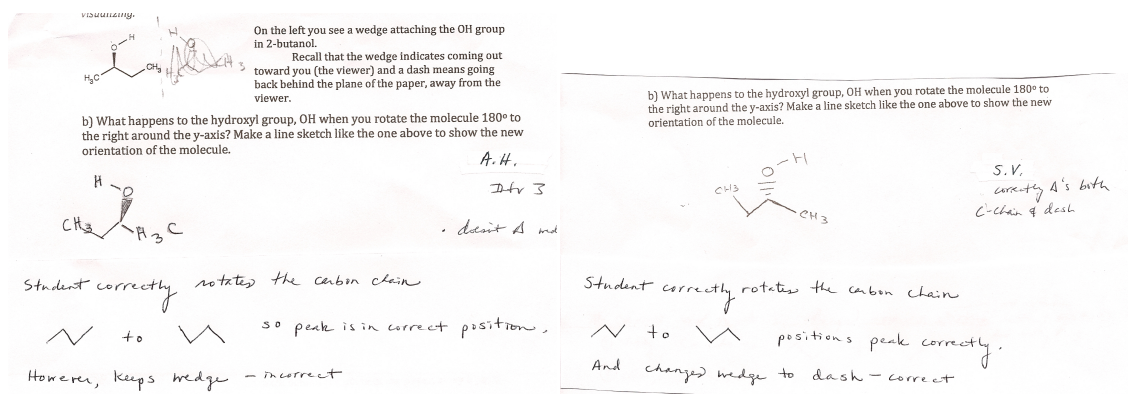


Figure 3.6 Intervention 3: Student Rotational Sketches

After this phase, I concentrated on specific questions that were used to focus my data collection. (Some examples of these questions are: How are students thinking? What elements appear to aid understanding? Identify student suppositions.) For example, when

coded and grouped, I noticed that students made comments that indicated they thought molecules were static entities (unmoving and fixed in position). This pattern gave me a window into student thinking, which led to the identification of a supposition (or belief) that students held about molecules based on their previous experiences, see Figure 3.7.

the hydroxyl group

Student asked question about relevance (A, H, I), "so if the model rotates 180° - will that change anything about its chemistry?" *Assumes - lack of movement*

OC: great Q he is not just "doing" but considering the why

Figure 3.7 Coded Note Suggesting Molecules are Static

During the selective coding phase of data analysis, relationships were identified as concepts were linked for understanding, thus leading to deeper interpretation. It was through this interpretive stage that I established meaning and causal relationships. For example, while considering student thinking about molecules as static entities, I linked that to other qualitative data showing how students adopted strategies to facilitate molecular rotation.

After coding and noting patterns in student comments that led to themes I grouped representative student comments (direct quotes) into tables that were useful in developing the story within the data. See Appendix J for examples. In the end, I used many large sheets of paper to sketch out a concept map/flow chart, which are reworked many times in many ways, helping to develop causal connections and relationships between the categories, allowing themes to develop.

b. Analysis of Interviews

Interviews were transcribed verbatim and they were coded in a very similar process to the field notes. I made a table that summarized student answers so that I could

easily refer to them. Interview quotes and observer descriptions were used to add depth to my understanding of how students were solving spatial tasks and importantly, whether or not students in the experimental group appeared to have improved skills. The interview transcriptions were particularly helpful in understanding how students were visualizing molecules, although this was limited by the students' ability to describe what they were seeing in their minds. Themes that emerged from the interviews were compared to the post-test results.

c. Analysis of Artifacts

The artifacts were coded for sketching accuracy to gain a sense of student understanding and progress during each intervention. Artifacts were used to develop ideas and hunches noted in the field notes during student participation in the interventions. Additionally, the artifacts were reviewed independently by lab section to see if any patterns emerged in which student work reflected understanding and difficulties. One area for which this procedure was useful was in considering how well students were able to add three-dimensional features to their sketches, such as symmetry planes, providing the researcher with details for future intervention design.

Overall, in keeping with the constructivist theory, I recognize that assessment is best done in the context of learning. Thus when considered collectively, the qualitative data offer the most authentic understanding of student learning through the intervention activities. By aligning the two data sources (qualitative and quantitative) I was able to triangulate some of the post-test findings, which allowed for a sense of whether students could transfer skills used in the interventions to test questions, where they were not allowed to use molecular models. If students could successfully answer the test questions

without visual and haptic information this would indicate that they had formed mental connections indicating learning had taken place.

3. Aligning Data

The findings of both data sets were analyzed for confirmations and contradictions to gain deeper insight and to assist in triangulation (Creswell, 2008). The researcher analyzed the performance of experimental and control group on individual post-test items. Questions on which the experimental group out-performed the control group by more than 10% were grouped by skills, which were related to the intervention themes. For example, identifying a symmetry plane included all questions that required students to identify a symmetry plane. The researcher took care to notice that improved performance took place for all questions, which had been grouped pertaining to a specific skill, such as symmetry planes. All themes were used as a guide to look at the individual interventions where students gained experience with these concepts. The qualitative data was used to develop the themes (illustrate and clarify), providing evidence of student engagement, practice, and understanding, establishing support that the interventions led to the improved performance of the experimental group on the post-test.

F. Reliability and Validity

My analysis and interpretations were informed by both qualitative and quantitative data sources, recognizing that a mixed methodology allowed me to capture an expansive understanding that will help to illuminate the role of the intervention activities in student spatial skill acquisition. To establish reliability and validity for a mixed methods approach I followed established parameters in both quantitative and qualitative research.

For quantitative validity standard measurements of statistical significance using p-values, effect size, and descriptive statistics were used to describe the results, as noted above in Data Analysis. The two sections of chemistry were selected and randomly assigned to each condition without knowledge of the intervention. A normal distribution was expected because each section had roughly 300 students drawn from the same student population. This allowed for the variance and means of each student population to be compared reliably. Other factors that improve the internal validity of this study include: 1) controlling for different teaching styles by using the same professor for both the control and experimental groups; 2) both groups took the pre-test and the post-test at the same time points during the course, holding the taught curriculum constant; 3) interventions were carried out in the same manner by each laboratory section and guided by the researcher in the same way, thus the intervention experience remained consistent throughout the different lab sections; 4) the researcher piloted these interventions with other chemistry students' prior to use with these groups to be sure these activities elicited spatial problem solving ; and 5) the undergraduate chemistry courses can be assumed to be a representative sample of the student body at the university, as they are open to all STEM majors, and therefore the study will have good external validity.

G. Gaining Entry and Informed Consent

1. Gaining Entry

The researcher wrote a proposal along with one of her committee members, a chemistry professor, and sent it via email to departmental faculty who taught general chemistry. Faculty replied favorably, and the researcher selected a faculty member based on the fact that they taught 2 sections of the same course. The researcher met with the

professor of the course at the end of the fall semester and again before the start of the spring term to discuss her research and to go over the pre-test. Next the researcher met with the laboratory coordinator to discuss the location and timing of the intervention activities during the students' laboratory period. The researcher was available for any questions and was not approached with concerns during the study.

2. Informed Consent

All students in both courses were informed orally and in writing about the study objectives, made aware of their voluntary participation, that they could choose not to participate without penalty, withdraw from the study at any time and confidentiality aspects; see informed consent form in Appendix L. Only students who signed and returned the informed consent form participated in the study.

Confidentiality

To ensure confidentiality of all written materials the researcher used pseudonyms and initials when referring to individual participants or their work. The researcher is aware that confidentiality is crucial in carrying out ethical research. She recognizes that “qualitative research is research in action and takes place in the field with real individuals living and working in the settings explored (Rossman and Rallis, 2012, pg. 73), and as such requires careful protection of participants confidentiality.

H. Researcher Profile

Throughout my growth as a teacher, particularly in the 90's, I came to view constructivist learning as the best way to educate. This was primarily due to the connections I developed with my students, and through discussions with colleagues, which provided unequivocal evidence that performance on tests, quizzes and labs often

did not reflect true learning. Further from a graduate course that I took in Philosophies of Education, at the University of New Hampshire, I became further convinced of the obvious fact that educational practice needed to be learner centered not teacher centered. John Dewey's emphasis on stimulating thoughts and questions in students rather than telling, which results in "smothering his intellectual interest and suppress his dawning effort at thought" (J. Dewey, 1926, Democracy and Education, p. 188) is key.

The researcher is herself an experienced chemical educator, her familiarity with the discipline facilitated her ability to recognize common patterns of learning, pinpoint unique ideas, note areas of confusion, and record important points that helped to discern the usefulness of the intervention. Allowing her to make informed next steps for effective spatial interventions.

CHAPTER IV

RESULTS

This chapter presents the results of the implementation of three intervention activities designed to develop students' spatial skills in general chemistry. The results of the data gathered to investigate the effectiveness of this intervention are presented below. This chapter begins with a presentation of the quantitative results of the post-test, including the effects seen by each successive intervention performed, and then moves through the themes identified based on the areas of skill development seen in the post-test. Each skill area that showed the experimental group scoring higher is developed and supported with results from the qualitative data in a manner that best addresses the research question. These areas are presented below in the following order: symmetry plane identification, visualization of molecules, and translation between 2D and 3D. *Note that all quotes and artifacts are representative for the topic for which they are presented.*

A. Post-Test Results

The post-test scores, shown in Table 4.1, indicate a significant difference with the experimental group scoring higher in comparison to the control group with $t(419) = 5.76$, and $p < 0.000$. A Cohen's d value of 0.56 confirms that the intervention had a moderate effect on the entire experimental group. This effect size needs to be considered in light of the fact that the experimental group was comprised of three groups of students each of whom participated to different extents in the intervention activities – participation in one, two or all three intervention activities. The research question can be best evaluated by comparing the results for the group of students who performed all three intervention

activities (n = 105) with those of the control group (n = 212), as shown in Table 4.2, for which $t(315) = 6.36$, and $p < 0.000$, and a Cohen's d of 0.75 indicating an effect size that is very close to large ($d = 0.80$), because these students received the most training.

Table 4.1 Post-Test Scores

Section	N	Mean	Std Deviation	p value
Experimental	209	7.28	2.56	0.000
Control	212	5.84	2.38	

A one-way ANOVA was used to test for differences among the three spatial interventions and the control group. Student performance differed significantly across the three interventions and the control group $F(3, 410) = 15.29$, $p = .000$. Tukey post-hoc comparisons of the four groups indicate that both students in the second intervention ($M=7.34$, 95% CI[6.59, 8.08]) and in the third intervention ($M= 7.74$, 95% CI[7.27, 8.21]) had significantly higher performance than that of the control group ($M=5.89$, 95% CI[5.61, 6.24]), $p = .001$. While each group showed an increase in their mean score, the 105 students performing all three activities showed a 2-point increase in their mean score when compared to the control group. See Table 4.2. These results show that the intervention activities were effective. Students in the experimental group scored higher on the post-test than the control group as a result of being engaged in repeated structured learning activities, allowing for greater skill acquisition.

Table 4.2 Post-Test Score by Intervention

Experimental: Number of Interventions	Total N	Mean	Standard Deviation	Effect Size
1	32	6.75	2.05	
2	50	7.34	2.60	
3	105	7.74	2.46	$d = 0.75$
Control	212	5.84	2.38	

Note: Six students in the experimental group and seven students in the control group took the post-test, but did not report their gender information.

B. Improved Skill Areas

While test score means show a statistically significant difference between the groups overall, a clearer understanding of student performance can be obtained from a comparison of correct item responses between two groups: the experimental group participating in all three intervention activities (n = 105) and the control group (n = 212).

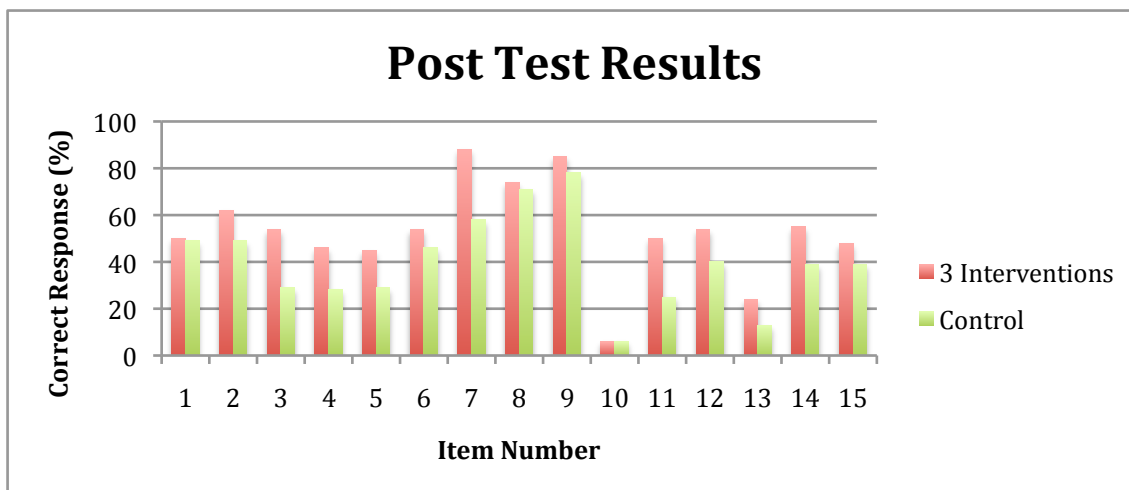


Figure 4.1. Post-test Results by Item

As depicted in Figure 4.1, the item that showed the greatest difference (> 15%) between the experimental group and the control group answering correctly were items 3, 4, 5, 7, 11 and 14, with several others (2, 12, 13, 15) showing (>10%) for the experimental group. Questions showing a stronger response rate for the experimental group were analyzed and grouped according to the skill focus of the interventions. As shown in Table 4.3, the areas that appeared to transfer well to the post-test items included identification of symmetry plane(s) for items 2, 3, 5, visualizing molecules (*mental imagery*⁴) for items 2, 4, 5, 7, 11, 12, 13, comparing molecular structures with dash/wedge cues (*visualizing*

⁴ Questions required possible use of mental imagery

*molecular orientation/mental rotation*⁵) in items 7, 11, 12 and 13, and translation between a 3D image and a 2D sketch with dash/wedge in items 14, 15.

Table 4.3 Test Items: Analyzed and Grouped According to Skill Focus

Skill Area	Post-Test Question									
	2	3	4	5	7	11	12	13	14	15
Symmetry Planes	X	X		X						
<i>Visualizing Molecules:</i>										
Mental Imagery	X		X	X	X	X	X	X		
Orientation					X	X	X	X		
Mental Rotation					X	X	X	X		
Translation									X	X

In summary, there were three areas of noticeable difference between the experimental and control group, which aligned closely with the skill focus of the intervention activities:

- Identification of symmetry planes
- Visualizing molecules – mental imagery, molecular orientation (MRT, comparison of structures)
- Translation between a 3D molecular model and a 2D sketch

Each of these areas will be discussed individually below weaving together the results of the qualitative data analysis of field notes, student interviews and student artifacts in support of the areas identified by the post-test. Qualitative data sources provide evidence of student engagement in the activities, illuminate student thinking, evidence of

⁵ Questions required possible use of mental rotation and visualization of orientation

knowledge construction, and when possible provide evidence of understanding that support the areas of skill development. Importantly, themes and categories will be developed to provide answers for the research question. Each area begins with a brief discussion of the post-test questions followed by supporting qualitative data.

1. Identification of Molecular Symmetry Planes

Post-test results show that a larger percentage of students in the experimental group were capable of correctly identifying molecules that contained a symmetry plane, scoring higher on questions 2, 3, and 5, as seen in Figure 4.1. Question 2 asked what is the maximum number of atoms that can lie within a plane of symmetry on a tetrahedral molecule, of carbon tetrachloride, CCl_4 . Questions 3 and 5 are shown in Figure 4.2.

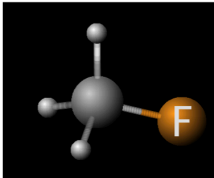
<p>Question 3</p> <p>Does <u>fluoromethane</u>, CH_3F, possess a plane of symmetry?</p>  <p>a) <u>yes</u> b) <u>no</u> c) <u>not sure</u></p>	<p>Question 5</p> <p>Does methanol, CH_3OH, possess a plane of symmetry?</p> <p>a) <u>yes</u> b) <u>no</u> c) <u>not sure</u></p>
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Figure 4.2. Symmetry Plane Questions: with and without 3D image

In question 3, 54% of the experimental group responded correctly, as compared to 29% of the control group. For question 5, the experimental groups' performance was 43% compared to 29% for the control. Note, the number of correct responses for the experimental group declined by approximately 10% (54% to 43%) from question 3 to 5, while the control group's response stayed exactly the same for both questions. Question 3

provided a picture of a 3D molecular model whereas question 5 provided only a chemical formula; it seems that the picture of the 3d molecular model facilitated the visualization process for the experimental group. The control group did not appear to benefit from the 3D picture.

The identification of molecular symmetry planes was an area of focus during the first and second intervention activities. An understanding of symmetry and symmetry planes was important for two reasons: 1) It helped students assess the 3D structure of a molecule for balance and evenness, which in turn helped them to grasp the important concept of molecular polarity; and 2) it provided students with a reference point from which to identify atoms belonging within a plane, allowing the relative in and out positions of attached atoms to become more obvious, and this assisted with sketching and dash wedge understanding.

To best appreciate how student understanding of symmetry planes may have come about requires knowledge of the intervention activities themselves, and Figure 4.3, shows the skill progression for the identification of symmetry planes during intervention 1 and 2, as designed by the researcher. Relevance for this skill was established through the concept of molecular polarity, which was related to a current topic being studied.

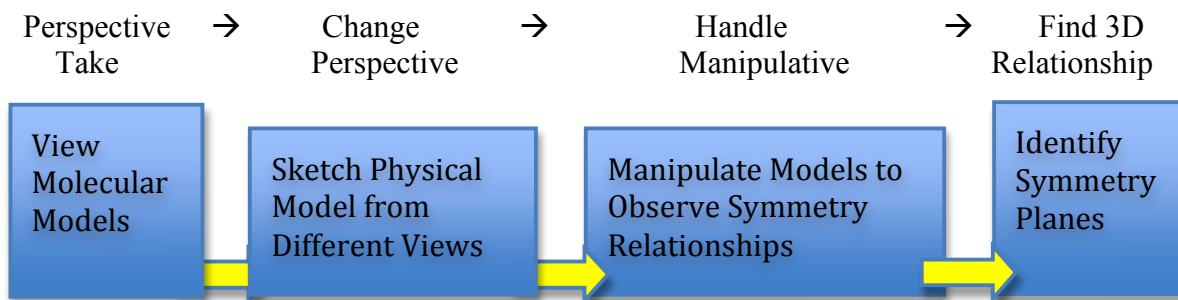


Figure 4.3. Skill Progression of Intervention Activities
Developing an Understanding of Symmetry Planes through Intervention 1 and 2 Activities.

At the start of the first intervention activity, the researcher both explained and demonstrated how to locate planes of symmetry using a hand held molecular model; this was repeated during the second intervention activity. Students gained first hand experience with this concept by viewing the structures of two molecular models, ethanol and butane. See Appendix D for intervention one, question 2. As students engaged in answering questions about symmetry they made comments about how the model looked:

“This one is symmetrical.” (M1 says) (and then F1 points to the model of butane and the two other group members are looking on) “Do you think it’s polar then?”(F1) “No.”M1 says.

*Students continue to discuss why it’s not polar, improving consensus within the group that perfect symmetry means no charge imbalance.
(FN, Intervention 1, Group 2, February 25, 2013)*

“ Slice it in half and you get 2 different halves. They are not the same” (F1)

Another says, “so the halves need to be the same?”(F2)

“I think so, because then they are symmetrical.” (F3)

(FN, Intervention 1, Group 1, February 26, 2013)

While viewing the ethanol molecule a student asks his group:

“Where could you move it to make it symmetrical?”(M1) One student reaches out and moves the molecule and another says, while pointing, “Yes, that way it looks symmetrical.” The first student says, “but not this way”(F1) and points to the middle of the ethanol molecule. (FN, Intervention 1, Group 1, February 25, 2013)

See Table 4.4 for the frequency of these observations in the field note data.

Comments such as these highlight the importance of perspective while viewing a molecular model for symmetry. From some directions the model looks symmetrical and from others it may not. Developing an understanding of how to find symmetry planes on a molecule required students to practice perspective taking.

a. Perspective Taking

During the activities students were guided by worksheet questions to view hand-held molecular models from different positions, e.g. the top, and from right or left sides,

Table 4.4. Field Notes by Intervention and Theme

Intervention 1	Themes			
	Symmetry Plane	Visualize Molecules	Translation Btw 2D & 3D	Sketch Molecules
Date: Feb. 25				
Group 3a	X			
Group 4a	X	X	X	
Group 5a	XX			X
Group 6a	X			
Date: Feb. 26				
Group 1a	X		X	
Group 2a	X		X	X
Group 7a		X		
Intervention 2				
Date: March 4				
Group 3b				X
Group 8b	X			X
Date: March 5				
Group 1b	X	X		
Group 4b	X	X	X	
Group 6b	X	X	X	X
Group 9b		X		X
Date: March 12				
Group 2b		X		X
Group 5b			X	X
Date: March 13				
Group 7	X	XX	X	X
Intervention 3				
Date: April 1				
Group 3		X	X	X
April 2				
Group 1		X	X	X
Date: April 8				
Group 2		X	X	X
Group 8		X	X	X
Date: April 9				
Group 6			X	X
Group 7			X	X
Date: April 10				
Group 4		X	X	X
Group 5		X	X	X

Note: X indicates that FN statement supports the theme.

which required them to change their egocentric reference frame such that their lines of sight varied. To begin, students were instructed to view down a bond, thus providing them with a specific reference point on the molecule. Observer comments note surprise and interest in students' voices as they discuss their observations with each other.

“Oh, how you see it depends on how you look! See what I mean?” (F1) (group member responds, M1) “Yes, I see it. If you look here (points) they are the same.” (another group member, M2) “Ok, yeah, you have to look in different places.” (Group discussion resumes). (FN, Intervention 1, Group 2, February 26, 2013)

“Well it looks different depending upon how I hold it! (F1, she goes on talking to group) “If I look at the side.” (she hastily sketches), “If I look at the top.” (She sketches again.) The 2 others are listening and looking at her sketch, they nod agreement. (FN, Intervention 2, Group 1 March 5, 2013)

“It depends on how you hold it, and how you look at it.” (M1 explains to his partners. They each take turns holding the models and passing them around. F1 responds) “Ok, yes I can see that. How do I know where to look?” (M2) “Yeah, how do we know?” (M1 says) “I think we have to show each other, (he points) so we all do it the same way.” Group starts sketching. (FN, Intervention 2, Group 2, March 12, 2013)

See Table 4.5 for the frequency of these comments in the field note data. Throughout the activities students became aware of how perspective influenced what they saw and to communicate clearly they had to be specific about from which perspective they were looking. During interviews students in the control group also made comments, which showed they had not previously considered how perspective provided different visual information. The control group comments reveal consideration of perspective and questions about how whether or not it should influence their answer.

“Well, I guess it really depends on where I am looking at the molecule. (She says with concern.) Does it matter where I look?” (Tina, interview, control group)

“I thought it just looked like this (points at the front of the model) but I guess I have to think about how it looks here.” (Points to the right side where the OH group is.) (Gabe, interview, control group)

Table 4.5 Field Note Frequency of Important Observations.

	Students express surprise and explain how to look, while perspective taking.	Models help with process.	Sketching from 2D to 3D and visa versa.	Dash/Wedge is difficult.	Symmetry plane identification is observed.
Intv 1					
Feb. 19	X		X	X	X
Feb. 25	X		X	X	X
Feb 26	X		X	X	X
Intv 2					
March 4		X	X	X	X
March 5	X	X	X	X	X
March 6	X	X	X	X	X
March 8		X	X		X
March 12	X	X	X	X	X
March 13	X	X	X	X	X
Intv 3					
April 1	X	X	X		
April 2	X	X	X		
April 3	X	X	X		
April 8	X	X	X	X	
April 9	X	X	X		
April 10	X	X	X		

Note: X indicates the occurrence of the important observation in field note.

Collectively, field note and control group interview observations show that perspective taking was a useful exercise to improve understanding about 3D molecular structures. In contrast, analysis of experimental group interviews shows that students did not consider perspective taking to be a new idea, rather they used it as a tool to answer questions, demonstrating an understanding of how to apply it to obtain their answer. Field note

excerpts below show how students in the experimental group efficiently use perspective to identify symmetry planes.

Student turns model instantly and points out her line of sight “cut it here, there is a plane.” She then turns the model and says “And this doesn’t have one, because it is off balance and uneven on that side.”

(Interview, Donna, experimental group)

“They would be (he points to the spot) attracted here.” Next student mentions “And if you think of it from here (points again to a different area of the model) the O on the OH group would be attracted to the H on this other molecule.”

(Interview, Nathan, experimental group)

Interviewer notes show that neither the experimental or control group students had previous experience using molecular models prior to the interventions, which indicates students had not previously practiced perspective taking.

b. Sketching Molecular Models

During the first intervention, students began the activity by making a free hand sketch of a 3D molecular model that they were familiar with, a tetrahedron, CH_2Cl_2 . This was followed by guided instructions about using dash/wedge cues to indicate the in and out of the plane positions for connecting atoms. Students were then asked to use these cues and re-sketch the same tetrahedron that they had done “free hand” at the beginning.

During the second intervention students were asked to sketch two familiar molecules, NH_3 and PF_5 , utilizing dash wedge notation, and student comments show that the use of dash wedge cues is new to them.

“The in out thing is hard” (F1)(student says while sketching). “It helps to look at the model because then you can see what is close and what is far away. That helps me understand it.”(F2) (FN, Intervention 2, Group 3, March 4, 2013)

“Hard to sketch, because I can’t decide what is out and what is back. It’s easier to imagine just one way.” (M2) Here student is referring to the fact that with a Lewis Structure a molecule looks “one way” i.e. static and w/model there are different ways to look so they felt it was harder to draw.

(FN, Intervention 2, Group 4, March 5, 2013)

*“Sketching it helps me to understand what it really looks like.” (F3) Her partner says, “but we really don’t use dash/wedge much.”
(FN, Intervention 2, Group 5, March 12, 2013)*

These comments show how students make meaning of the dash/wedge cues through the process of sketching molecular models.

c. Manipulating Models

Models were used throughout the intervention activities as a concrete 3D object (referent) that would provide students with the opportunity to directly interpret the spatial positioning of atoms within a molecule, allowing for a deeper sense of molecular structure. When learning to sketch and look for symmetry planes students had to determine which atoms were within a plane, and thus could be positioned flat on paper. As the quote below shows, the physical models assisted with this by allowing students to directly observe planar relationships, instead of trying to imagine them.

During the identification of a symmetry plane, student holds the model up in front of her eyes and says “I try to keep it parallel to my vision, so I can only see the number of atoms in a plane. I need to hold it and look at it from my own (here she puts emphasis on “own”) line, so that I can tell.” (What do you mean your own line?) “My own line of vision that lets me see if the atoms are in a plane.” She holds the model and points while explaining “these go back so these three are straight in line.” Here the student describes the literal way in which the model allows her interpret the spatial information. (Beth, interview, experimental group)

Once the planar relationships were identified the relative positions of atoms in and out of the plane became more obvious to students.

Students found models to be quite helpful when trying to understand directionality of bonded atoms, and they continued to be used for this purpose by most students for all three interventions:

*“If you put it like that it is coming towards you. If you put it like this (student moves the model) it is going back.” The “it” is a hydrogen atom.
(FN, Intervention 1, Group 5, February 25, 2013)*

*“Ok, with models I really see it.” (F2) She points to the plane.
“It’s hard to look at the sketch and tell but with models when I move them it is easier to see.” (F3) Group is discussing how to find symmetry planes for question 2. (FN, Intervention 2, Group 6, March 5, 2013 Group 2)*

See Table 4.5 (page 73) for the frequency of these comments in the field notes.

d. Identifying Symmetry Plane(s)

Perspective taking and model use came together to help students consider the number of symmetry planes a molecule contained. Students brought together their collective understanding to discuss this idea:

*“Is there only one symmetry plane?” student (M1) asks his group. Student (M2) says “Yes, just cut it in half when looking like this” (he points). Student (F1) says, “What if you turn it? And look here?” she points. After discussion, students’ decide there are 2 places to look.
(FN, Intervention 1, Group 6, February 25, 2013)*

After identifying planes of symmetry using the molecular models, students were asked to draw them into their sketch. Figure 4.4 shows some examples of student work for the ammonia, NH_3 molecule during intervention two.

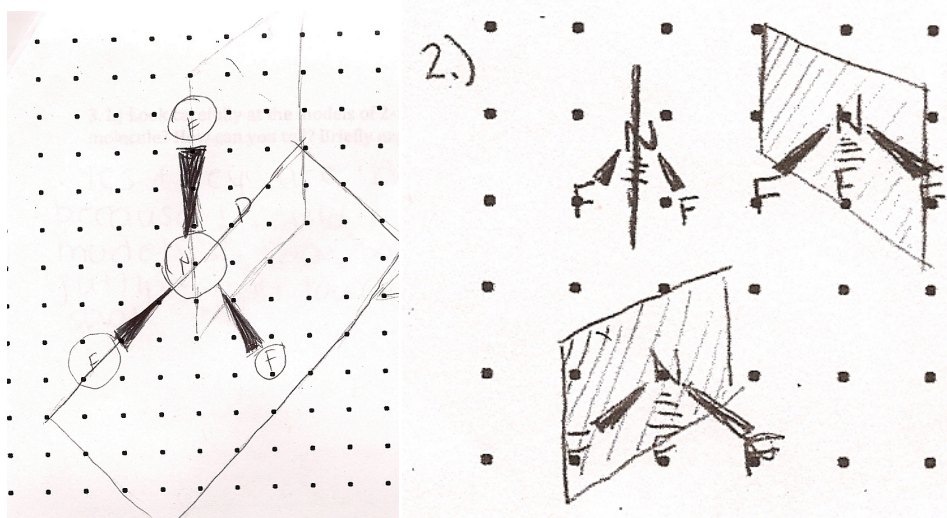


Figure 4.4. Symmetry Plane Sketches: Examples of student work

Analysis of artifacts showed that about half (50%) of the students required a number of re-sketching attempts to represent the plane(s) of symmetry (see Table 4.6), and this provides evidence that it was challenging for them. The fact that students made a number of re-sketching attempts also shows that they put effort into making an accurate sketch.

Table 4.6 Frequency of Re-sketching Attempts in Artifacts (Section Wed. Odd)

Question 2b) Sketch 2 lines of symmetry for each molecule.		
Yes	No	N/A
30	32	5

Yes = re-sketched, No = not re-sketched, N/A = did not add sketch symmetry planes

In walking around I see several students in each group making a second sketch, some that have the symmetry plane positioned more clearly, others that make use of diagonal lines to show sectioning.

(FN, Intervention 2, Observer comment, March 5, 2013)

“How do I draw a symmetry plane through PF₅ on paper?”

(FN, Intervention 2, Group 7, March 13, 2013)

In three of the 5 groups I observed students looking at each others sketches, deciding whose were better, and redrawing their own to copy the one they thought looked best.

(FN, Intervention 1, Observer comment post-activity, February 25, 2013)

The process of sketching a symmetry plane added three-dimensionality to sketches, which helped students represent more detail in the positioning of atoms, see Figure 4.5. After successfully identifying symmetry planes on a molecular model, students require practice representing them in their sketches. The researcher noted that they had to think carefully about how to represent this new aspect of three-dimensionality in their sketches. Students benefited from peer examples while learning how to do this.

“Yours looks good, I understand it. Mine doesn’t make sense.” She then proceeds to re-sketch. (FN, Intervention 2, Group 8, March 4, 2013)

One student is helping her partner to make a sketch “You have too many carbons.” She points at the model and counts to show her partner what she means. (FN, Intervention 3, Group 5, April 10, 2013)

Having the students include the symmetry planes in their sketches allowed for a better three-dimensional representation as well as providing a window into student interpretation, and this was used to gauge student understanding.

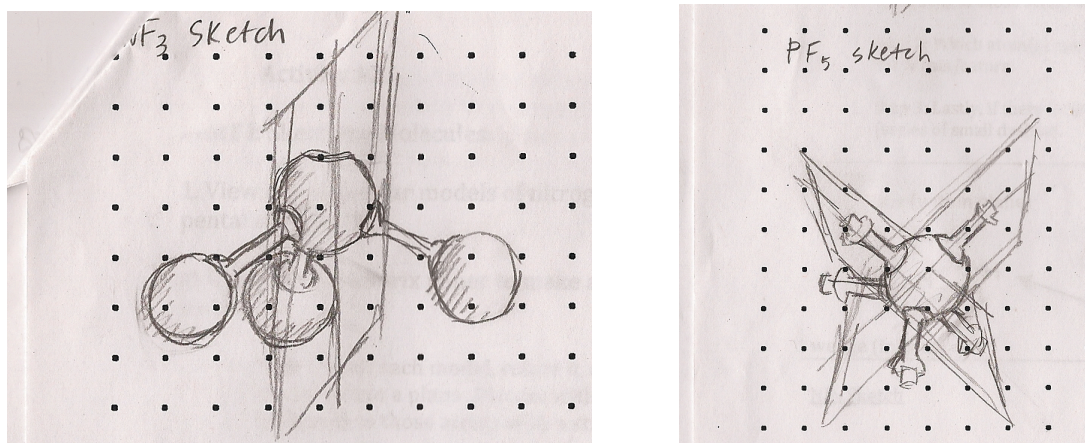


Figure 4.5 Student Free-Hand Sketches with Symmetry Planes

Interview data showed that almost all (9/10) students were able to successfully identify a plane of symmetry, while looking at a hand held molecular model of ethanol in question 2d). See Appendix G for interview questions. All students who participated in the interventions were able to identify the plane almost immediately while the control group required more prompting and took much longer to assess the molecule and respond.

Excerpt of observation during interview with a student in the experimental group: He reaches out and turns the molecule so that the C-C chain is facing toward him, and points saying “yes, if you look down this way.” He is pointing out his sight line. This student answers instantly without the need to move the model around and look at other positions. (Andy, interview, experimental group)

Observation of control student who could not identify the symmetry plane: She looks at the molecular model of ethanol on the bench and then picks it up. She does not rotate it, considers it in the same position it was in initially. She shakes her head “I don’t think so.” She then turns it slowly and says, “It’s hard to tell.” I ask her why and she says “Well because there are different ways to cut it in half.”

She continues to stare at it she then says, "I don't think so because it's not even." She does not sound confident. (Tina, interview, control group)

See Table 4.7 for the occurrence of this theme in the interviews. Of the two control group students, one of them successfully identified the symmetry plane after taking a while to manipulate the model in different directions. This supports the notion that students need to view the model in different positions, and that the sketch did not provide enough information for them to answer confidently. During interviews students were also asked to identify a plane of symmetry by looking at a 2D sketch without the use of a molecular model. In this case, the majority of the experimental group students (7/8) were able to do this successfully, but none of the control group students (0/2).

Table 4.7 Interviews: Informants and Themes

Informants	Themes			
	Symmetry Plane Identification	Visualized Molecules	Translated Btw 2D & 3D	Sketched Molecules
Andy	X	X	X	X
Annie	X	X	X	X
Beth	X	X	X	X
Lynn	X	X	X	X
Ned	X	X	X	X
Ted	X	X	X	X
Will	X	X	X	X
Donna	X	X	X	X
Gabe (Cntrl)	X	X	X	X
Tina (Cntrl)		X		X

Note: X indicates statements or representations made by the informant that support the theme during the interview.

2. Visualizing Molecules

The post-test results indicate, that the experimental group was able to compare molecular structures and identify similar molecules more successfully than the control group. Four post-test questions (7, 11, 12, 13) asked students to compare molecular structures. Doing this successfully required mental rotation of one or both of the structures and/or the ability to imagine the molecules from a different sight line by mentally changing their egocentric reference frame. Experimental group students had practice comparing similar 2D molecular structures containing dash wedge cues in both interventions two and three, and these skills showed some of the greatest difference between the experimental group and control group scores. To begin, data for the four post-test questions will be discussed, followed by a description of student experiences with the intervention activities.

a. Bilateral versus Vertical Comparison

Post-test questions 7 and 11 were similar in structure as shown in Figure 4.6.

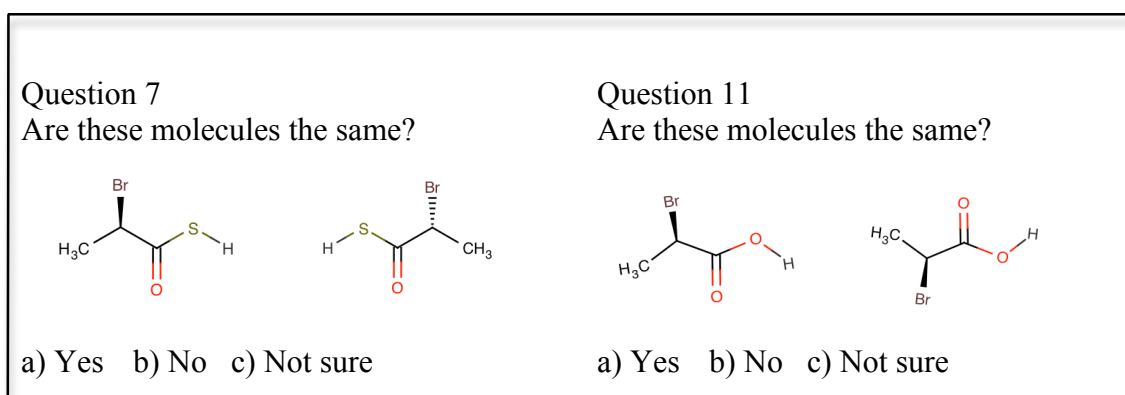


Figure 4.6 Rotation of Molecular Structure

Both questions assessed for understanding of dash/wedge notation as well as a comparison of molecular orientations. The first comparison question, Question 7, was the most straightforward because both molecules were oriented in a manner that allowed for easy comparison. The red double bonded oxygen atom was used to draw the eye to similarities in structure and orientation. The rotation of either molecule to the right or the left by 180° around the y-axis would position the bromine, Br atoms so that they would match.

In contrast, question 11 involved rotations up or down around the x-axis and the carbon-to-carbon chain was not oriented in the same direction for both molecules. Question 11 was specifically placed later in the post-test allowing for confirmation of students' skill for visualizing molecules and conducting rotations in their mind. In this case, the carbon-to-carbon chain orientation is making a W on the right and an M on the left. The red was used to draw the eye to the differences in orientation. Regardless of whether students rotated the structure on the left so that the double bonded oxygen was positioned up, or whether they rotated the structure on the left so the double bonded oxygen was positioned down, in both cases the bromine atom would be positioned back behind the carbon chain. In this case a 180° rotation about the x-axis resulted in the bromine atom being back behind the carbon chain thus not matching the other structure, which would have the bromine atom coming out from the carbon chain toward the viewer as indicated by the solid wedge. Although question 11 was harder for students to assess as shown by the substantial decrease in correct responses of the experimental group from 88% correct in question 7 to 50% correct for question 11, still half of the students

answered the question correctly supporting the effectiveness of the interventions on students' skill development.

In each of these questions students were asked to visually compare the structures of two molecules, see Figure 4.7. These results show that both groups of students found the assessment requiring a vertical comparison in question 11, more challenging than bilateral comparison in question 7.

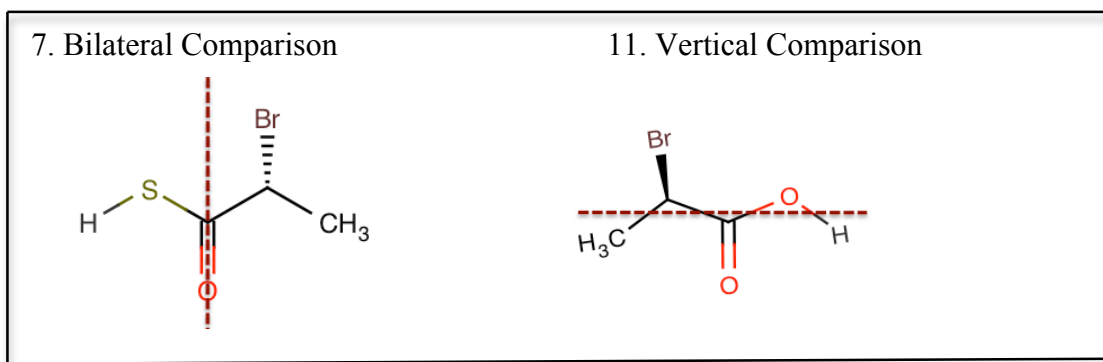


Figure 4.7. Bilateral vs Vertical Comparison

Question 7 required students to bilaterally compare the molecular structure, from each side of the dashed line, and question 11 required students to make vertical comparisons from above and below the dashed lines. Questioning why vertical comparisons were more difficult the researcher chose to research artistic features of image balance, based on her own artistic background and found information from a photography web site (Suler, J. n.d. Symmetry. Retrieved from <http://users.rider.edu/~suler/photopsy/symmetry.htm>) that discussed how much easier it is to assess symmetry from side to side which is believed to be due to the positioning of our eyes. Finding balance in an image requires photographers to assess images from top to bottom in a manner similar to that needed to

assess molecular structure. Photographers also find this is challenging until they acquire experience with this aspect of balance.

b. Cyclic Structures

Although cyclic structures were not part of the intervention activities, the experimental group also showed better skills in the rotation of cyclic molecular structures (Q12: 54% to 40%; Q13: 24% to 13%), when compared to the control group, see Figure 4.8. Question 12 required students to rotate the molecule clockwise or counter clockwise within the plane of the paper, while question 13 required two rotations, one out of the plane and another clockwise or counter clockwise within the plane.

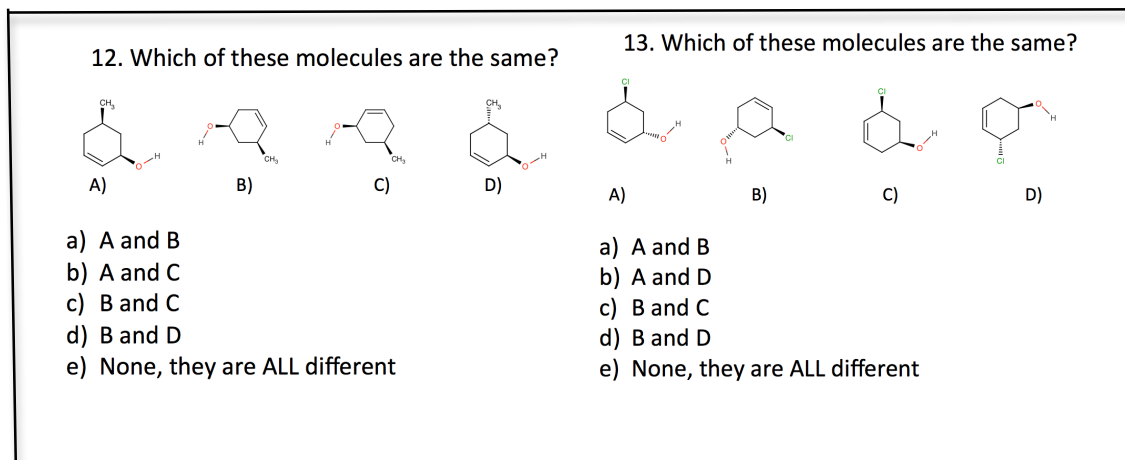


Figure 4.8 Molecular Comparisons with Cyclic structures

The results show that about half of the students in the experimental group successfully answered question 12, while only one quarter of them responded to question 13 correctly. This suggests that more rotations make comparisons more challenging. Nevertheless the experimental group was more successful than the control group indicating that the

intervention activity had some effect on students' skills, although only one rotation was practiced. How the interventions provided experience and practice with molecular comparisons will be discussed below.

c. Comparisons Using 2D Sketches and Molecular Models

During the pilot study it was noted that chemistry students used inefficient comparison strategies and had a difficult time with simple comparisons of molecular structures (Carlisle, 2012). Based on this result the intervention activities were focused on strengthening students' ability to assess structural features of molecules as well as the orientation of these features in space. The first step in the process asked students to view 2D sketches with dash/wedge cues and determine whether the molecules were the same or not, see Figure 4.9. This process required students to carefully consider the orientation of one molecule and compare it to another. Answering question 3a) in intervention two, required students to imagine how one molecule could be rotated to achieve the orientation of the second molecule.

Question 3a. Are these molecules the same?

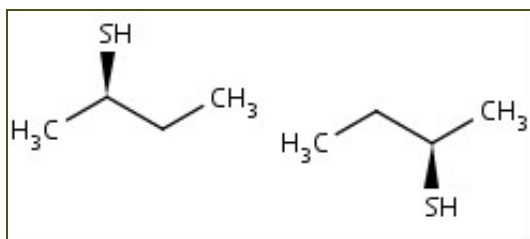


Figure 4.9 Comparison of molecular structure:

Anticipating that this skill may be challenging for students I used this first step to create dissonance, raise questions, and establishing relevance for the activity. Observer comments in field notes and artifacts help to describe students' initial experience.

Students in several groups discuss their ideas, deciding the structures are not the same, this appears to be the popular response, which is incorrect. Students

describe how they would manipulate the structure on the left to arrive at this answer. Of the groups I observed today many (5/4) decide the molecules are not the same. (FN, Intervention 2, Observer comment post-activity, March 4, 2013)

“Rotate the SH group of the molecule on the left down to match the one on the right.” They then describe turning the structure by 180°, such that the SH is positioned near the end of the molecule instead of the beginning. Students note, that this causes the SH group to go to the back, and they conclude that the molecules are not the same. (FN, Intervention 2, Group 4, March 5, 2013)

*“You turn it.” Says F1. “How?” (F2) “To the right 180°”(F1) “But then the SH is in the back.” (F2) “Yeah, so they are not the same.” (F3)
(FN, Intervention 2, Group 6, March 5, 2013)*

*Another group discussing “You turn it (points to the molecule on the left) so that the SH group is on the right.” (She points to the SH on the left molecular structure.) “And then you flip it down.” Another student says, “Ok, yeah that works. So they are the same, right?” she says, “Yes, I think so.” This group arrived at the correct answer by using two rotations.
(FN, Intervention 2, Group 9, March 5, 2013)*

Groups 1 and 2’s explanation would mean that the SH-group has a dash attached to the carbon chain instead of a wedge, which would result in a different arrangement in space because the SH is back behind the plane of the paper. Although students had the right idea of how to rotate the molecule, they incorrectly interpret the new position of the SH after the rotation.

Another interesting aspect of this exercise was that it revealed students’ thought about the SH group being attached to a different carbon atom. In the structure on the left it appears to be in the 2nd position⁶, while in the one on the right it is in the 3rd position, see Figure 4.9.

Observing groups perform Intervention 2, question 3a, students thought that the SH group was attached to a different carbon atom. Discussion reveals that they interpret the carbon on the left (H₃C) and the carbon on the right (CH₃) as

⁶ The zig-zag carbon chain is numbered from left to right, starting with the carbon in the H₃C group.

different due to the way the hydrogen is written, i.e. either before the C or after the C. This is an important detail to note.

(FN, Intervention 2, Observer comment, March 5, 2013)

Student artifacts also reflect this thinking. For example, students wrote “Not the same, because the SH group is attached to a different C.” This comment indicates that students are not thinking about the connectivity of the atoms, they are literally interpreting the picture as represented.

Two students were observed rotating their paper while considering whether or not the molecules were the same, which was yet another way to think about the comparison.

1st group female student looking at questions on paper, I see her turning the paper in different directions while looking at question 3a. Later in group 4, I see another female student showing her partners how to rotate their papers to view the sketch from different positions.

(FN, Intervention 2, Observer comment, March 12, 2013)

This observation shows that students found it challenging to rotate the molecules mentally and then compare them. A review of student artifacts showed that only 24/78 students correctly answered question 3a) from intervention 2, see Table 4.8.

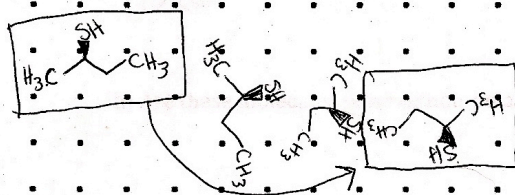
Table 4.8. Frequency of Correct Response to Question 3a and b

Question: 3a (Tally = 78 students)	
Are these two molecules the same? (Using sketch)	
Yes	No
24	54
3b) Are the molecules the same? (Using models)	
Yes	No
76	2
Students Changed Answer on Artifact	
52	--

Note: Yes = molecules same, No = molecules not same.

Another way to scaffold the rotation process used by students, besides turning their paper, was to make a sketch. Figure 4.10 shows an example of student work.

3.) ~~They are not the same because the SH complex is branching off of separate carbons within the~~
 Just kidding, I realized those were both ^{identical} CH₃ complexes on each end and so one can be c
 by flipping over the other one because the flip will maintain the SH complex's positio
 coming out of the paper.



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Figure 4.10 Student Sketch of the Rotation Steps for Question 3a.

Next, in part b) of question three, students were provided with the two physical molecular models, of the sketch shown in figure 4.9 and asked the same question again, “are these molecules the same?” Student artifacts show that the use of a manipulative allowed students to compare the structures more successfully in part b, with 77/78 students responding correctly, see Table 4.8. Further inspection of artifacts showed that 67% of students (52 /78) changed their answer to part a) after working with the hand-held molecular models, as shown in Figure 4.10, where the student drew a line through her original answer. This indicates that the wedge cues in the sketch were not effective in assisting student visualization while comparing molecular orientation. At this point, the students benefited from the use of models. These results are supported by the following comments:

Watching and listening while students manipulate the models to make them look the same “If you flip it, you only see one.” F1 shows this with the model, and F2 comments, “Oh, ok.” (FN, Intervention 1, Group 7, February 26, 2013)

“If you rotate it this way” (M1 rotates the model) “they look the same” Another student in the group disagrees and says “well, no, because if you rotate them like this (M2 moves the models) they look different now.” (OC: Next F3 joins in and they take turns looking and discussing ultimately deciding they are the same.)

(FN, Intervention 2, Group 2, March 5, 2013)

“If you look at it this way (demonstrates) and then you turn it counter clockwise, it looks like the other molecule.” (M1) Group watches and agrees making comments and trying it themselves. (FN, Intervention 2, Group 1, March 6, 2013)

*“Ok with models I really see it. It’s hard to look at the sketch and tell, but with models when I move them it’s easier to see.” (F3)
(FN, Intervention 2, Group 5, March 5, 2013)*

Group 1 student comments to researcher directly “The models really help to clear up any uncertainties, and this makes me feel more confident with my answer in part a.” (FN, Intervention 2, Group 7, March 13, 2013)

The quotes above support that students found it helpful to manipulate the models while comparing structures, and that they engaged in discussing the changes in orientation with each other.

Question four of intervention 2 asked students to make another comparison using only a 2D sketch example with dash wedge cues to see if they could transfer what they just learned in question three. Student artifacts show that about half (38/78) students were able to correctly answer the question without the use of molecular models, this shows a 20% increase when compared to initial attempt on question three where only 30% of the students answered correctly.

d. Visualizing Rotations with Molecular Models

Practice with comparing molecular structures and visualizing molecular orientation was further built upon during the third intervention, which was designed to provide explicit experience with molecular rotations, and it incorporated gesture as part of the process. This activity asked students to perform rotations about the x or y-axis with a physical molecular model, and then to make a sketch of the new orientation using dash wedge notation. See Appendix F for intervention three questions. Asking students to

make a sketch of the new orientation required them to carefully assess how the rotation caused the positioning of atoms to change. Field notes capture students' conversation as they engaged in this process.

"It looks like this (student points at rotated model) now will it look different after we draw it?" (M1) He is referring to question 2 b) and c). Another student replies, "It will look the same as the other one because of the 180° rotation."(F1) "It doesn't matter which way you turn it."(F2) "Yes, right I can see it now, but didn't realize it."(F3) Students look at each other's sketches to see if they are the same. (FN, Intervention 3, Group 1, April 2, 2013)

For question 2, student points and says, "I think it looks just like this."(F1) Student responds and says, "Well yes if you rotate it around the y-axis." (F2) Another student says, "Yes just compare how it looks here," (M2) (He points to the sketch.) "and imagine how it looks turned around the axis." (FN, Intervention 3, Group 2, April 8, 2013)

"It doesn't matter which way you turn it." Student rotates the molecular model. "Yes, right I see it now, but I didn't before." Student needed to observe and do the rotations in both directions to see that the end result was the same. Many students took their time here and rotated the model several times forward and back. (FN, Intervention 3, Group 3, April 1, 2013)

While listening to a group of three students performing the rotations for question 1 one student says, "If I did not have the model I could not see that the rotations are the same." Another one nods in agreement and reaches out while asking to hold the model. (FN, Intervention 3, Group 4, April 10, 2013)

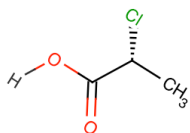
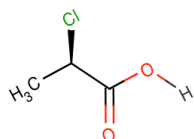
"Up carbon, down carbon, up carbon, look at the chain." (F1) "Now turn it to the left."(F2) "It looks like the other one now." (F3); All students seem to agree. Now they rotate the model again, but to the right. F2 says, "it doesn't matter it will look the same no matter if you turn it right or left." Students F1 and F3 say together "Lets do it anyway." and F1 "Yes, it helps me to look at it." Student F2 either has stronger skills or has come to understand more quickly, while F1 and F3 really make it clear that they want to see the rotation. (FN, Intervention 3, Group 5, April 10, 2013)

These comments reflect students' needs to view the rotation process with the manipulative. Observations show that students in each group took the initiative to hold the actual model and rotate it themselves. Students did not simply watch others and then make a sketch; only after rotating it themselves did they make their sketch. Comments

show that through the process of model manipulation students realize that some rotations yield the same molecular orientations, indicating that this was not immediately obvious to them. Using the model appears to make students feel more confident in their reasoning process and helped them to interpret the necessary structural information to make accurate comparisons; their willingness to sketch only after they tried the activity supports this.

Interview data allow for a more in depth understanding of student thinking while comparing molecular structures. Interview questions 5 and 6, see Figure 20, were closely correlated to the question previously discussed in the intervention activities and to the post-test questions that were used to assess for this skill. During interviews students made comments that allow for some insight into differences between the experimental group and the control group while answering these types of questions.

Question 5



Question 6

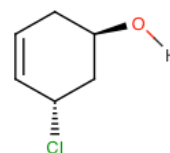
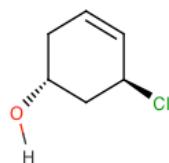


Figure 4.11. Interview questions 5 and 6a.
(Models were *NOT* available to facilitate problem solving.)

For question 5:

“The Cl bond switches from coming out at you to going back behind. I see the double bonds and think about how to match them up.”

(Andy, Interview, experimental group)

“Initially my brain goes straight to the differences in the picture, like the Cl. So the wedge would be coming out, where with the lines it would just be rotated at a different angle. They are definitely the same.” (how can you tell?) “Because they all have the same bonding. The different bonds to the Cl just indicate that it is basically flipped. In my mind I can flip it over and it would look exactly like that.” She points to the structure. (Annie, interview, experimental group)

“They are the same. Just flipped 180° around the y-axis, this one is facing front,” She points to the left structure. “and this one back. The rest of the structure is the same, so when I turn it, the front and back line up.” Gets it quickly.

(Donna, interview, experimental group)

“So by the structures I can immediately see that the CH₃'s are on opposite ends and I need to flip one, but I also need to consider the Cl's. I would flip it over, and they would be the same.” (Beth, interview, experimental group)

“I don't think they are the same. If they were the same and just facing different directions... humm”(What are you thinking?) “Well I am trying to imagine if I had a mirror, if one would look like the other one. No, they are not the same, because one Cl is forward and the other one is back.”

(Tina, interview, control group)

For question 6:

“They are the same. What I did to answer this (he points to structure on the left) is I rotated 1/6 of a turn so the Cl was facing downwards and then I flipped it over the y-axis.” (Why did you flip it over?) “Because this OH is back and I need to bring it forward. Flipping it over will change the positions they are in. It's like thinking about it from the back. Peeking behind the paper.”

(Ned, interview, experimental group)

“This I would rotate around the x – axis.” (And he rotates toward himself.) “Here is x-axis and just flip it over.” He turns his pen toward himself, using his pen as manipulative because he doesn't have a model – gesture.)

(Will, interview, experimental group)

Tentative conclusions may be drawn from these comments keeping in mind that only 2 students from the control group participated in the interview process. The comments above reveal articulate responses from the experimental group showing that it was easy for them to explain their spatial reasoning process. This was the case with all but one student in the experimental group, who did not participate in the third intervention. The experimental group also had noticeably shorter response times. This is likely due to their better understanding of dash/wedge cues, as evidenced by their comments, and their familiarity with 2D representations from the activities. The interview comments show

that students in the experimental group not only performed transformation tasks with ease, but that they could confidently rationalize their process.

e. Visualizing and Mental Imagery

Question 2 on the post-test, required students to imagine the molecule CCl_4 , which possesses a simple tetrahedral geometry, in their minds eye, and then correctly identify the number of atoms within a symmetry plane. The experimental group correctly answered question 2 more often than the control group (62% to 49%). Questions 4 and 5, see Appendix B, also required students to work with molecular structures from memory, in each case the experimental group outperformed the control group.

Students spoke of “*seeing it in their heads,*” while performing the intervention activities together, which indicates the use of mental imagery. Of the data sources collected, the interviews provide the best insight into student thinking when attempting to “visualize in their minds eye” because students intentionally explained their reasoning, while field note comments also provide support that students are engaging in this type of thinking. When and how do students visualize molecular shape in three-dimensions? To begin, interview data lends some insight for how they tend to think about molecules when presented with a simple 2D Lewis Structure⁷.

Is this molecule polar?

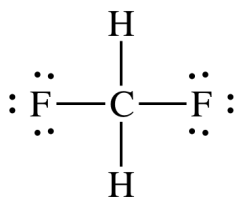


Figure 4.12. Interview question 1, Lewis Structure for CH_2F_2 .

⁷ Lewis dot structures are representations that show the bonding between atoms of a molecule as well as the lone pairs of electrons that are present on atoms in a molecule.

Four out of eight students (50%) in the experimental group responded that CH_2F_2 was non-polar when provided with the Lewis structure shown in Figure 4.12. Students commented:

“I tend to picture it in 2D.” Student looks at the physical model of CH_2F_2 and says “that is not how I was picturing it. I thought it was more T’ed with 90° angles.” (Beth, interview, experimental group)

“The bonds are pulling equally against each other so balanced and nonpolar.” (Lynn, interview, experimental group)

“Symmetrical and no lone pairs on the central atom, so it’s nonpolar.” (Donna, interview, experimental group)

The molecule is in fact polar, and when shown the molecular model 3 of the 4 students who answered incorrectly, recognized this right away. When determining the polarity of a molecule, such as the one in Figure 21, students need to have an understanding of the spatial relationships between the bonded atoms. It was noted that when students used molecular models during the activities they thought that molecular polarity⁸ changed with view.

“This one is polar when you look at it from the side, here,” student points “but it looks symmetrical when you look from this side, so nonpolar.” Another student agrees with her saying “Yes, so maybe it’s both.” (FN, Intervention 1, Group 3, February 25, 2013)

Groups discussing “If you cut the molecule like this (she points to it) it is symmetrical. But then if you look at it this way... it looks polar.” (FN, Intervention 2, Group 4, March 5, 2013)

Both of these comments suggest that polarity changes with view, which underscores the need for students’ to view and manipulate three-dimensional structures, at the same time

⁸ Molecular Polarity is a term used to describe a molecule with a partial charge imbalance that results in parts of the molecule having a partial positive and partial negative charge which greatly influences it’s reactivity with other molecules.

that they are learning about the concept of polarity. Being able to consider geometric structure in 3D would provide students with a better understanding of polarity.

One goal of the activities was to have models assist in the formation of accurate mental images for some common molecules and atom arrangements, so that when models were not available students could effectively reason through questions that required spatial knowledge. Interview question's 5 and 6a (see Figure 4.11 pg. 90) detect how students employed mental imagery because students' had to describe their thinking without the use of a molecular model to assist them.

Control students:

*For 2d symmetry plane: He describes "Being able to rotate it in my mind, thinking about it like a picture and then rotating it."
(Gabe, Interview, experimental)*

*For 5 "I don't think they are the same. If they were the same and just facing different directions – trying to imagine if you had a mirror – this would not be the same because one Cl is forward and other is back. That is the discerning point."
(Tina, Interview, control)*

Experimental students:

*"I like to think that I have a little bit of a photographic memory. When I am taking tests or especially when I am doing this kind of stuff. I just take a snapshot in my mind and then I can manipulate it so that I can view it in a different way in my head so then I can rewrite it in the new way. So yeah I feel like that helps me a lot." So you rely on your spatial skills quite a bit? "Yes definitely, most definitely. Most times it's that that lets me answer these questions rather than my actual knowledge of chemistry." She laughs. (No kidding, ok!)
(Annie, Interview, experimental)*

"So by looking at the structures I can mentally look at the order that the atoms in the molecules are in and um I can immediately see that methyls are on opposite ends – so you would need to flip one, but also have to consider Cl's. I can picture this in my mind. But to explain... Let me think – if you take the molecule... This one is coming towards me and the other one is in the back. Lets see. If I take the molecule and flip it over (she gestures) then Cl is still in the back and then I would have to rotate it backwards – yeah." (Beth, interview, experimental)

*“They are the same – just trying to think about how to describe the rotation.”
Based on where the line is... hard to explain, but I can visualize it in my head.”
(Donna, interview, experimental group)*

These student comments reveal that students do use mental imagery to consider tasks that require rotation, however for most students explaining what they are imagining is difficult.

In addition, the researcher noted that during their explanations for questions 5 and 6, seven out of eight experimental students gestured as well as one of the two control group students. It seems as though when students try to reason without a molecular model they need to gesture with their hands. These comments help to understand how students think when they are asked to perform a task that requires some visual imagery.

3. Translation Between 2D and 3D

During the intervention activities students learned to interpret 2D sketches with dash/wedge cues through the use of molecular models. All three interventions provided practice with this skill.

a. Post-test Data for Translation Skills

The post-test results show that about half of the students in the experimental group were able to interpret the information provided by a picture of a 3D molecular model and relate it to a 2D sketch as compared to about one-third of the control group (see Figure 22). This ability to go back and forth between different external representations will be referred to as “translation” for the purposes of this study. Translation was an important area of focus in this study because the pilot study demonstrated that students had difficulty interpreting the spatial information provided in

a 2D sketch, and therefore could not use this information for reasoning. While this was an important skill development area, it was difficult to assess with the multiple-choice post-test format, because true 3D molecular models were not available for student use. During the post-test, students were asked to reason with the pictures of molecular models shown in Figure 22, while these provided some 3D information and possible priming, they were presented in 2D. However, these questions did probe students' spatial knowledge of common bond angles as well as the dash/wedge notation used to represent the orientations. Qualitative data below shows student experiences with the translation skill.

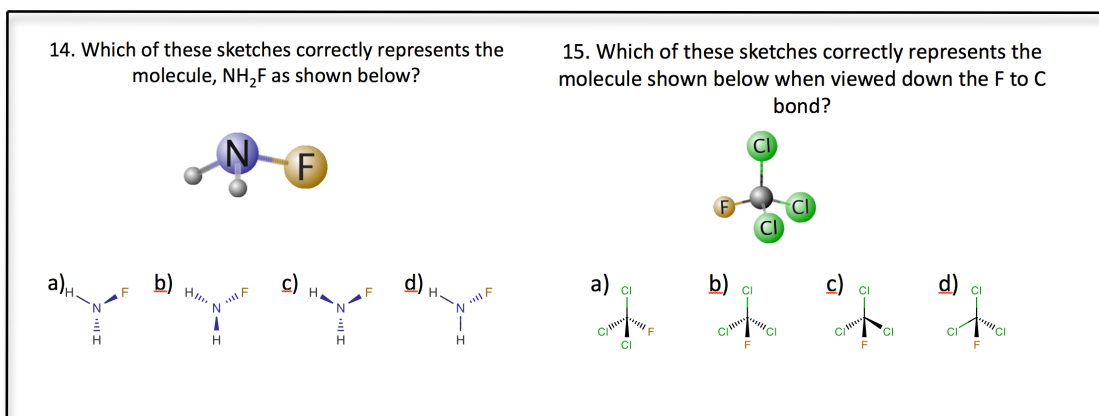


Figure 4.13 Translation from 3D Model Picture to Sketch with Cues

b. Experiences with Translation Activities

Students were asked to view molecular models and make sketches of what they saw in each of the three interventions. In this way, students gained experience looking at 3D molecular structures and practiced representing the 3D information in a 2D sketch. They also used 2D representations with dash/wedge cues to make associations to 3D molecular models thus working back and forth between a model and a sketch. The aim was to develop student understanding such that they could transfer this knowledge and use it to create, or recall, a 3D image in their mind while looking at a 2D sketch with dash

wedge cues. The qualitative data describe how students gained experience translating spatial information.

i. Intervention One

The qualitative data show that students worked progressively through the translation process, starting with the simple application of dash wedge cues to represent three-dimensionality in the first intervention.

“How do I show that the atom is behind while the others are out at me?” (F2) says to her group. One group member points to the picture with dash/wedges on the handout. F2 takes her time and sketches the molecule. I looked at her sketch and it was good. I think she needed reassurance that she was doing it correctly. (FN, Intervention 1, Group 3, February 25, 2013)

While observing, students in two separate groups comment that they have seen dash/wedge but never used it before.

*“I have seen dash/wedge, but never used it.” (F1)
(FN, Intervention 1, Group 1, February 26, 2013)*

As students were learning to sketch, during intervention 1, important aspects of their thinking were drawn out as they began to represent a molecular model. For example, when looking at the sketch provided on their worksheet for intervention one, shown in Figure 4.14, students had questions about how the sketch looked relative to the model.

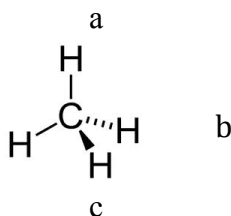


Figure 4.14. Dash/Wedge Representation of Methane.

“How come it is close when you draw it (points at 2D sketch on his paper), and when I look they are further apart?” Student observes that the model shows the atoms at equidistant positions, and that the sketch makes them look closer together in some areas and further apart in others. Group member says “that’s what the dashes and wedges are for.” (F2) Student replies “Maybe they should be spread out more.” (M4) (FN, Intervention 1, Group 4, February 25, 2013)

This student is noting the distance between the atoms a and b, versus b and c on the sketch in Figure 4.14 and is comparing it to the molecular model in front of him. His group discusses this while they make their sketches. This comment suggests that making a sketch from a molecular model helps students gain a more realistic sense of the information sketches actually provide. The information in the sketch does not literally translate into three-dimensions unless students know VSEPR Theory. The sketch in Figure 4.14 is a typical representation found in textbooks, exams, lecture etc. and it is worthwhile to clarify the 3D information implied in the sketch.

ii. Intervention Two

During the second intervention, students were challenged to rationalize the differences between 2D molecular sketches, and to locate symmetry planes on common molecules. Both of these processes require reasoning with both a sketch and a model, creating a need for translation.

“These are the same.” Student points to the sketches in 3a. “Because I flip it and it looks the same.” Student uses models in 3b to rationalize the 2D sketch in 3a. In this case the student does a direct translation comparing the structure of the model to the sketch. (FN, Intervention 2, Group 3, March 4, 2013)

“Ok, with models I really see it. It’s hard to look at the sketch and tell, but w/models if I can move them it’s easy to see” Group discussing how to find symmetry planes for question 2. Student is finding it hard to obtain information from the sketch, prefers model. (FN, Intervention 2, Group 6, March 5, 2013)

The comments above indicate that students find the kinesthetic aspects of the model beneficial, and that they are beginning to reason with both the sketch and the model together. To answer the questions necessitated students to translate their understanding of the 3D relations in the molecular model to a 2D sketch, which gave meaning and relevance to this skill. The utility of the model appeared to encourage students to transfer

their understanding of spatial information from the model to the sketch to obtain their answer. Data shows that they did not rely on the sketches to provide their answers.

Models were particularly helpful while learning about symmetry planes. Students used them to find the symmetry planes in 3D and then had to think about how to show them in their 2D sketches as the comments below demonstrate:

“How do I draw a symmetry plane through PF_5 on paper?” student says to her group while looking at the molecular model. Student proceeds to draw referring back to the model often. (FN, Intervention 2, Group 7, March 13, 2013)

Student working on question 2. “Its harder to find symmetry planes while looking at the sketches.” (F2) She proceeds to point to the model and explain to her group why she finds it challenging. “I can see it here” she points “but it’s hard to show it using dash/wedge, because of how the atoms are attached.” Another group member shares their sketch with her so that she can see how they did it. (FN, Intervention 2, Group 6, March 5, 2013)

While students practiced drawing in 3D during intervention 1, question 2 shows that it was not immediately obvious to the student how to represent what she was looking at. Examples of student sketches with symmetry planes are shown in Figures 4.4 and 4.5. The need to represent the symmetry plane provided students with a reason to translate what they were able to see and understand with the models. Re-sketching attempts noted in the identification of symmetry planes category were shown by student artifacts to be useful reflecting student made progress through this experience. Student comments also show progress in applying their understanding of orientation (in/out) to the dash/wedge cues while using models.

Student (F1) points “Now I am starting to understand how to look at the model.” Other group member (F2) “Yeah, it helps me to understand the dash/wedge.” (FN, Intervention 2, Group 5, March 12, 2013)

“I am used to using the models now, so it’s quicker to get the information.” Student comments to group while making her sketch. (FN, Intervention 3, Group 6, April 9, 2013)

iii. Intervention Three

During intervention three students were asked to place the molecular model so that it was positioned like the sketch on their worksheet, which required them to translate the sketch cues and use them to assess the orientation of the model. Prior to this activity students had only been instructed to reason from the model to the sketch, whereas here they were reasoning from the sketch to the model. Students' comments indicate that students find it easier to translate information from a sketch to a model. The comments made below suggest that the information is easier for them to assess and reason with.

Watching first groups of students place the model like the sketch for question 1. It helped me to see where they were at in their thinking by watching how they did this and the comments they made. Watching first group of students place the model like the sketch several made comments about how this helped! "This really makes sense now that I can see it (points to the sketch) with the model." (F1) "Yes, the comparing really helps." (F2) Here student refers to comparing between the sketch and model. Another group "Ok, I can see this now." (F3) "The models help the sketch make sense." (F4) Students appear to appreciate this simple question making positive comments. (FN, Intervention 3, Group 7, April 9, 2013)

"So it originally was like this, (She holds the model and points.) but then this is down." She points to the sketch. Her group members agree and one takes the model and positions it by themselves. (FN, Intervention 3, Group 8, April 8, 2013)

Watching a new group of 3, 2nd round of students. They move through 1a positioning the molecular model correctly and 1b sketching new orientation with little trouble. Some discussion of how it looks on paper vs in the model. One of them said that it was incorrect to position the OH group down, but the other two explained it was relative to the tetrahedral angle and pointed to the sketch. (FN, Intervention 3, Group 5, April 10, 2013)

Watching students perform manipulations provided a window into their understanding of the translation process, and thus, made for an excellent formative assessment tool. These comments suggest that students have constructed knowledge about the translation process, because they are readily reasoning between the model and the sketch.

Students also practiced molecular rotations during the third intervention. Students used models to perform rotations about the x and y-axis and then cross referenced this information to their sketch and/or made a new sketch after the rotation. Students engaged in this process with interest. Comments below refer to questions 1a-1e. See Appendix F.

“They are the same right?” (Looking at question 1b) and c) group member says, “ I think so.” Another says, “Yes the same.” I notice 1 pair of students decide to do the rotations again to double check. Second male student rotates to right and then back to the left. Partner says, “Yes, definitely.” Now they sketch. (FN, Intervention 3, Group 6, April 9, 2013)

“If I did not have the model I could not see that the rotations are the same!” I watched her with her partner. Student held the 2-butanol and rotated it horizontally from the starting position in both directions – toward and away. She did this several times, about 5 and then says, “No, it doesn’t matter.” to her partner, who was watching and agreed. To “see” it she had to repeatedly look and rotate the model before she felt confident. Her partner tried it too and then they worked with another girl sitting next to them, who was in another group. I wondered initially if students would find this unnecessary... so it was good to see them be engaged, and patiently reasoning through the questions. (FN, Intervention 3, Group 4, April 10, 2013)

Upon doing the rotations with the model, students were able to assess the orientation of the molecule successfully. Comments also revealed that students did not “short cut” the activity by looking at the 2D sketch provided on the handout and mentally rotate it to get the same information. They used the models as instructed, and comments show that students benefited from rotating the models. The process of rotating the models complements gesturing, which may improve understanding. The field note data above show that students compared direct positioning of atoms from the model to the sketch, which indicates that they were becoming more skilled at translating the information.

Data collected during interview question 6, see Appendix G, provides further evidence that students were capable of translating information from a sketch to a model, and visa versa. Students were asked to compare two 2D sketches with dash wedge cues

and decide if they are the same without a molecular model in part a). They were then provided with molecular models and asked to explain their answer.

“They also are the same. (He answers quickly.) “What I did to answer this is I rotated this one on left (student points to molecule on paper) 1/6 of a turn, so Cl was facing downwards and then I flipped it over the Y axis and ” (Why did you flip it over?) “Because this OH is back and I need to bring it forward. Flipping it over the axis will change the positions they are in. It’s like thinking about it from the back. I think of it like looking behind the paper. This is how I try to think of it actually.” (Ned, interview, experimental group)

(I pass the student the molecular models and ask, “Is there a way you could test to see if the molecules are the same?”) She says, “Yes, position them the same way.”(She takes the models, rotating until the Cl’s are in the same place on the ring, and then flipping. I ask her to explain her process, so I can capture it verbally, and she says “It’s just intuitive. I move them around so they look identical. Except the Cl, but that does not matter, right? It’s just the way the pieces are put on.” (Can you explain?) “Not really, I just look and I do it.” (Student did well figuring it out, but appears to find it difficult to explain.) (Lynn, interview, experimental group)

Both students in these interviews translate from the sketch to the model effectively. Both are able to position the model and arrive at the correct answer that they are the same.

However, Ned does not have trouble explaining his reasoning, while Lynn appears to find her process challenging to describe.

The translational process is about students taking what they understand with models and making appropriate associations to the information in a 2D sketch with dash/wedge cues. The data show that students were attentive and focused during these activities indicating that they found them useful and engaging. All the data indicate that models help to interpret 2D representations with dash wedge cues, thus molecular models played a mediating role in the translational process.

CHAPTER V

DISCUSSION

This section begins with a review of the research question, followed by an overview that specifically addresses how the data support the research question. The interpretation of the findings, including supporting literature, addresses four areas: the identification of symmetry planes, sketching, visualizing molecules and the role of translation. Additional findings are interpreted that have instructional relevance for spatial skill development. These findings relate to: student misconceptions, post-test development, and a model for spatial skill development. Subsequently, implications for practice are discussed, followed by the strengths and limitations of the study. The discussion closes by suggesting directions for future research.

A. Research Objective

The objective of this study was to gather data on intervention activities designed to develop students' spatial reasoning skills. The research question was intentionally broad due in part to the fact that the literature lacks examples of how to develop students' spatial reasoning skills and to allow for a broad exploration of ways in which the intervention may have been helpful to students. The goal of the research was to implement and evaluate some new activities for general chemistry, designed to increase student awareness of the spatial features of molecules, establish the relevancy of learning spatial skills, and to help students acquire the spatial skills necessary to support their learning.

B. Overview

The results show that students enrolled in a large lecture section of the second semester of general chemistry, and who participated in intervention activities specifically designed to strengthen their spatial skills, scored higher on the post-test assessing spatial ability than a control group. Three short activities performed approximately every three to four weeks during the semester allowed both male and female students to develop spatial ability. In particular, post-test results, identified three areas in which participants developed their spatial skills: 1) symmetry plane identification, 2) visualization of molecules, and 3) translation between 3D molecular models and 2D sketches. Students who engaged in multiple learning opportunities (all three interventions) earned higher post-test scores. The results show each additional intervention lead to further improved skill acquisition.

Qualitative data analysis identified several ways in which the spatial interventions supported student learning of spatial skills. First, qualitative data allowed for an understanding of how students participated in and learned from the spatial activities, thus clarifying how the activities led to skill acquisition in the three areas mentioned above. The results show that the visual and kinesthetic features of molecular models facilitated working between all skill areas, with students particularly benefiting from tactile manipulations. These findings led to the development of a model for chemistry students' skill development, which will be helpful for the teaching and learning of spatial skills. Importantly, these qualitative findings will also assist in the future development of intervention activities.

In addition to the three areas identified from the post-test results, three student misconceptions related to the 3D spatial features of molecules were observed: 1) students' thought molecular polarity changed with view, 2) that molecules were static entities, thinking of them in one stationary position, and 3) students tend to think of molecules as flat, based on their familiarity with Lewis Structure representations. Recognizing these misconceptions will be helpful in addressing the learning of chemistry concepts requiring spatial knowledge.

C. Interpretation

The results of this study show that students' spatial skills are malleable and can be developed with practice. These results also suggest that it is worthwhile to incorporate guided activities into students' classroom or laboratory experiences. The results of this study are in line with the findings of other studies (Coleman & Gotch, 1998; Ferguson, 2008; Sorby, 2009; Taagerpera & Arasasingham 2011; Terlecki et al., 2008) also demonstrating that spatial ability can be improved upon with training.

Although research has suggested that training and practice for how to use and interpret information in external representations allows for the strengthening of accurate internal mental images and improves ones ability to visualize (Cohen & Hegarty, 2007; Mohler, 2008), there have been very few, if any, empirical studies focusing on this. This study demonstrates that training with external representations can be beneficial for spatial skill development, specifically for visualization and the translation of information from 2D to 3D. This study also contributes to the recognized need for spatial training studies lasting for a semester or more (Uttal & Cohen, 2012; Wai et al., 2009).

The four primary areas, in which students were shown to develop spatial skills will be described below.

1. Sketching: Making External Representations

Each intervention activity required students to make sketches using dash/wedge cues, and as such sketching played an integral role in student understanding. Kozma and Russel (2006) identified the development of “representational competence” as an important step in students’ becoming chemists. The results show that the intervention activities strengthened students’ abilities to accurately represent molecular structures. During this process students’ benefited from the opportunity to practice making their own sketches, and from looking at each others’ representations. Specifically, the data show that students learned from re-sketching attempts that were made following observation of their peer’s drawings. This suggests that collaborative work in this area would be particularly beneficial.

Further, it is important to note that confusion was seen when students were asked to interpret dash/wedge cues using a molecular model (see Figure 4.14, pg. 97), and students needed reinforcement during each intervention activity. Analysis shows that it was worthwhile to take instructional time and clarify the 3D information implied from a 2D sketch with dash/wedge cues, because these types of representations are commonly found in textbooks and are often used during instruction. The data suggests that the implied spatial information is not obvious for students.

During the interventions sketching was used to show what students were seeing and to reflect their thinking, when viewing a molecular model. As mentioned previously, the need to make a sketch focused the students’ attention causing them to look carefully

and more analytically than they might have done without the need to create a sketch. It also allowed students to practice representing what they were “seeing in their heads” allowing them to have useful conversations about perspective.

When studying the process of transformational reasoning through drawings, it has been suggested that for diagrams in science, which carry significant conceptual content, there may need to be a transition from the visual realism stage where students draw “what they see” to one where they draw “what they know (or have learnt).” (Ramadas, 2009, p. 306).

The important role of sketching will be further discussed throughout each of the themes.

2. The Importance of Identifying a Symmetry Plane

In the literature the identification of a symmetry plane has been shown to be an important area for developing spatial abilities for two reasons: First, it can be used to assist in the translation process between 2D and 3D representations and second, it can be used as an analytic strategy to facilitate the identification of chiral molecules and isomers in organic chemistry. When employed by experts symmetry planes have been shown to be an efficient analytic strategy, because there is no need to visualize and mentally rotate molecules. Such an analytic strategy decreases cognitive load and facilitates the spatial reasoning process (Harle & Towns, 2011; Stieff, 2010; Taagerpera & Arasingham, 2011; Wu & Shah, 2004). However, Taagerpera and Arasingham’s (2011) study found that the identification of symmetry planes on simple organic molecules was quite challenging for students in an introductory organic chemistry course despite practice with molecular models. The identification of symmetry planes came late in these novice students’ knowledge structures, although textbooks and experts portray this strategy as an “easy” way to determine whether molecules exhibit chirality or are isomers of each other. My

findings confirm that symmetry plane identification is not easy, and that students require training. Several guided activities in this study focused on symmetry plane identification and the relationship of symmetry to relevant conceptual areas such as polarity and intermolecular forces. In contrast to Taagerpera and Arasasingham's (2011) study, my results show that students were able to use these strategies correctly. Because students in the experimental group were better able to identify symmetry planes than students in the control group suggests that the skill progression shown in Figure 4.3 on page 69 was effective. Through the use of activities, which guided students to view molecular models from different lines of sight, students came to better appreciate the 3D nature of molecules. Sight lines created understanding of spatial relationships between the bonded atoms of a molecule, which may not be immediately obvious to the untrained observer. The process of viewing and sketching from different perspectives set students up for the task of locating a symmetry plane(s).

This activity was explicitly designed to guide students through the process of changing their egocentric reference frame as a step toward the mental rotation process, by looking at these different sight lines, students develop an understanding of how their view changes in each position, helping them to gain a sense of how turning the model would provide each of these different views. Understanding this would help them to consider mental rotation, which they may later use with a mental image as their experience progresses. The results show that students looked carefully from different positions; thus, locating a symmetry plane created the need for students to use the perspective taking that they had just practiced. At this point, some students found it easier to pick up the model, rotate it, and view it from different perspectives, while others continued to keep the

model stationary on the bench top and moved their heads around it. This was an important feature of the activity, because for some students it was beneficial to their reasoning process to be able to return to a specific position by moving their heads back to the same place. For these students, being able to compare atom positioning related to specific egocentric reference frames was more concrete, and removed a level of abstraction that would be introduced when using the process of rotation. It is important to mention that as might be expected with a large group of students, this process was more intuitive for some than for others. However, for all students the steps laid out in the activity appeared to be helpful in assisting them to reflect on their thinking, thus making their thinking process clearer and developing meta-cognitive skills. Research has shown that spatial reasoning may be inherently egocentric in nature causing students to adopt a different “view point” or frame of reference in order to transform an object-based allocentric representation into an imaginary egocentric framework (Wallentin et al., 2011).

As mentioned previously, an important reason for the development of symmetry plane identification was that it helped students to establish a frame of reference for the location of specific atoms within the plane, and therefore allowing them to concretely observe which atoms were going behind the plane and which were coming out at them. In this way, symmetry plane identification facilitated students’ ability to make an accurate sketch with 3D dash/wedge cues. Throughout the three interventions students’ representational skills were refined as this critical skill was slowly developed.

Another unique feature of the intervention activities that appeared to support student understanding of symmetry planes and three-dimensionality was the use of dot

matrix paper during intervention two. The dot matrix paper helped to provide depth to an otherwise flat 2D sheet of paper (Sorby, 2009).

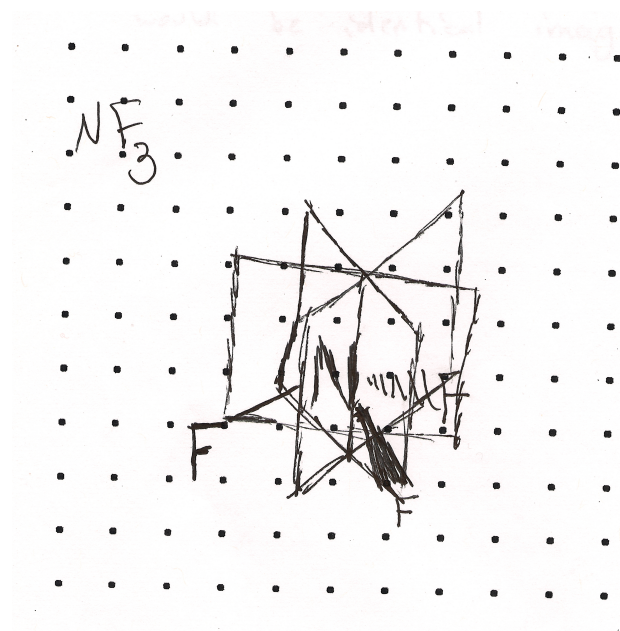


Figure 5.1 Use of Dot Matrix Paper to Enhance the Meaning of Dash/wedge Cues.

Figure 5.1 specifically depicts how the student positions the symmetry plane to be coming out with the wedge and be going behind with the dash. Use of the dot matrix paper to scaffold the sketching process, helped students in two ways: 1) the dots assisted students in making their lines straight, which helped them to add precision to their sketches; and 2) through the addition of a symmetry plane to their sketches the dots enhanced three dimensionality, which enhanced students ability to represent directionality, thus the dots enhanced the meaning of the dash/wedge cues as also depicted in Figures 4.4 and 4.5 on page 76.

3. Visualization of Molecules

Other important findings of this study relate to students' skill in visualizing molecules. In this area, the experimental group scored higher than the control, indicating

that they were more capable of mentally rotating molecules, visualizing molecular orientation, and using mental imagery. Several features of the interventions appeared to assist students in the development and use of internal representations. First, with respect to learning how to visualize molecular orientations, the interventions were structured so that students were guided through molecular comparisons, first with a 2D sketch and then with 3D molecular models. Recognizing that students are often asked to make comparisons only in 2D, the activities incorporated 3D models to help students' reason through the comparison process. Use of the molecular models appeared to strengthen these processes by providing a 3D visual aid as well as tactile/kinesthetic features to aid in spatial understanding. Second, students practiced performing rotations with physical molecular models, which helped them to visualize how to mentally rotate a 2D sketch by allowing them to make associations from the atom positioning in the physical model to the atom positioning in the 2D sketch. The rotational process with a physical model also complemented students' natural inclination to gesture.

a. Molecular Comparisons

Molecular comparisons were introduced during intervention two, questions 3a) and b), see Appendix E. The results showed that 67% of students' who were initially incorrect in their comparisons of 2D sketches, were able to correctly compare molecular structures in 2D *after* having the experience of rotating a molecular model and making comparisons in 3D as part b) of question 3 prompts them to do. A simple explanation of these findings may be that the 3D models clarified the atom positioning as indicated by the cues contained in the 2D sketch. However, the way in which students were guided through this process played a role in their level of understanding as well. Asking students

to make initial comparisons with only the use of a 2D sketch raised questions and established relevance, because it required them to interpret the spatial information embedded in the representation. The data showed that this was a challenging task, for which students employed scaffolding strategies (turning their paper, making a sequential sketch, and gesturing; see Figure 4.10 page 87). The students approached part b) of question 3 wanting to see if they were correct or to figure out the answer. In part b) students were provided with two molecules, one to rotate and another to leave as a stationary comparison. Having two models of the same structure allowed students to go back and forth between the two, while checking for similarities and differences, without having to hold one structure in their working memory and remember it while also making comparisons. How students' reason from a model to a sketch will be further discussed under the next section the *role of translation*.

b. The Number of Rotations

A related finding that surfaced during observations of the comparison/rotation process for question 3a and b) in intervention 2, was that some students made one rotation to achieve the target orientation shown by the other molecule in the sketch (see p.84, Figure 4.9), while others made two rotations to achieve the same positioning. This may lend some important insight into why the mental rotation process increases the cognitive load. Two rotations required more working memory space for some students who did not see that the matching could be accomplished with one rotation. This was a point of interest noted during the pilot study as well (Carlisle, 2012). Research has shown that one difference between high and low spatial ability, is the ability to mentally rotate structures, with low ability students often experiencing cognitive overload (Weckbacher

& Okamoto, 2012). Training that improves students' ability to assess orientations without rotation could be very helpful in this area. Moreover, these results suggest that training could be accomplished through practiced rotations using molecular models, where students could watch the orientation change as they turn the molecule, which facilitates students' comprehension of the mental rotation process required by 2D representations.

c. Gesture

During the third intervention, gesture was built into the activities by asking students to perform specific rotations with the molecular models. The findings show that it was beneficial for students to hold and physically turn the molecular models while performing rotation tasks, thus mimicking the movement they might make, if they were gesturing during the mental rotation reasoning process. It is thought that, because gesture can depict movement, it focuses an individual's attention on the transformation itself, thus improving their ability to mentally transform spatial information (Ehrlich et al., 2006). The findings in visualizing and mental imagery, where students did not have use of molecular models indicate that practicing gesture through the physical manipulation of molecular models may be an effective instructional technique.

d. Post-Test Findings

The analysis of the post-test showed two findings related to students' ability to visualize molecules and make comparisons that required mental rotation. First, it appears easier for students to make bilateral (side to side) comparisons of molecules than vertical (top to bottom) comparisons. The post-test results show a 35% drop in correct responses for both the experimental and control groups when asked to compare molecular orientations from top to bottom vs. side to side. These results should be considered in the

development of instructional strategies by providing students with more practice with vertical comparisons. This finding also raises awareness of the fact that spatial comparisons are not all the same, and that there may be other cognitive facets involved in learning related to visual perception and encoding.

Second, the results show that when students were asked to identify similar molecules, and the target orientation required more than one rotation, the correct response rate decreased by half, suggesting that students would benefit from further training that scaffolds the process of two or more rotations. The intervention activities only allowed students to practice manipulations requiring one rotation, and even when performing these tasks, the qualitative data show that students used strategies (rotating paper, sketching, and using a pen or other manipulative to gesture) to facilitate their reasoning through the rotation process with a 2D sketch, instead of mentally rotating the molecule. Students may have been able to employ gesturing while taking the post-test, but they did not have had time to sketch nor did they have a written question on paper to rotate.

4. The Role of Translation

Translation mediates the role of different external and internal representations, helping students to interpret the specific meanings embedded in different spatial representations. The post-test findings in this area show that students in the experimental group were better able to identify the correct dash wedge positioning that corresponded to the picture of a 3D molecular model than the control group. The qualitative data show that students had significant practice interpreting spatial information, while working back and forth between external representations, during the interventions. Student comments

revealed that sketching, while looking at a 3D molecular model, was a unique experience. The findings show that during the intervention activities, students came to realize what the sketch cues were actually implying while sketching from a 3D model. Students' previous experience with representations had been mainly comprised of copying sketches, not creating them, or to look at sketches shown in their textbook while reading to understand conceptual information. Students often copy sketches with little real understanding of the meaning of the 3D cues. The process of creating a sketch was an important part of the translation process. Drawings and sketches "are considered as external representations that facilitate operations on internal mental representations (Ramadas, 2009)," therefore the ability to make accurate sketches integrates the translation between external representations and the use of visualization for internal mental representations.

During each intervention, students repeatedly and without any prompts, used molecular models to clarify the spatial relationships presented in the 2D sketches. This simple finding has important implications for classroom practice: 1) Instead of showing a model and describing it during VSEPR Theory instruction, students should have the opportunity to use the molecular models themselves, and 2) students need to use molecular models consistently to reinforce spatial relationships. This study showed that students required training with simple geometric shapes that they had already been exposed to several times throughout the year. Clarifying the cues on simple molecular structures will support student understanding as molecules grow in complexity (Wu & Shah, 2004).

Translation is a process that needs time to develop – it needs practice. It required different amounts of time for students to become comfortable working back and forth between what they saw using the molecular model and what they were able to represent and or associate to the same molecule represented in 2D. Students were able to locate symmetry planes much more easily with a molecular model, and this created a need for students to focus on the translation process, so that they could represent on paper what they were able to see using a model.

During the third intervention activity, students applied their translational skills to work back and forth between a sketch and a model, while rotating molecular models and sketching the new orientation. At the beginning of this activity students were asked to position a molecular model such that it matched the orientation of a 2D sketch with dash/wedge cues. Watching students place a molecular model in the same orientation as a sketch proved to be an excellent formative assessment tool that will be useful for instructors. Placing the model like the sketch showed whether or not students understood dash/wedge notation, and the amount of time a student needed to accomplish this showed whether or not their thinking process was still in a formative stage. Additionally, this allows students to demonstrate rather than verbalize their spatial reasoning, which may provide a truer window into their understanding, as verbal descriptions may be a more difficult way for many students to show their understanding (Lohman, 1994; Schwartz & Heiser, 2003; Stieff, 2010; Wai, 2009).

5. A Model for Spatial Skill Development

The goal of this research was to implement and evaluate some spatial activities. Based on the results, a model, shown in Figure 5.2, was developed to describe the way student skill acquisition took place during the intervention activities. This model identifies three skill areas that need to be addressed in order to effectively assist chemistry students with their spatial skill development: Visualize, Sketch, Translate.

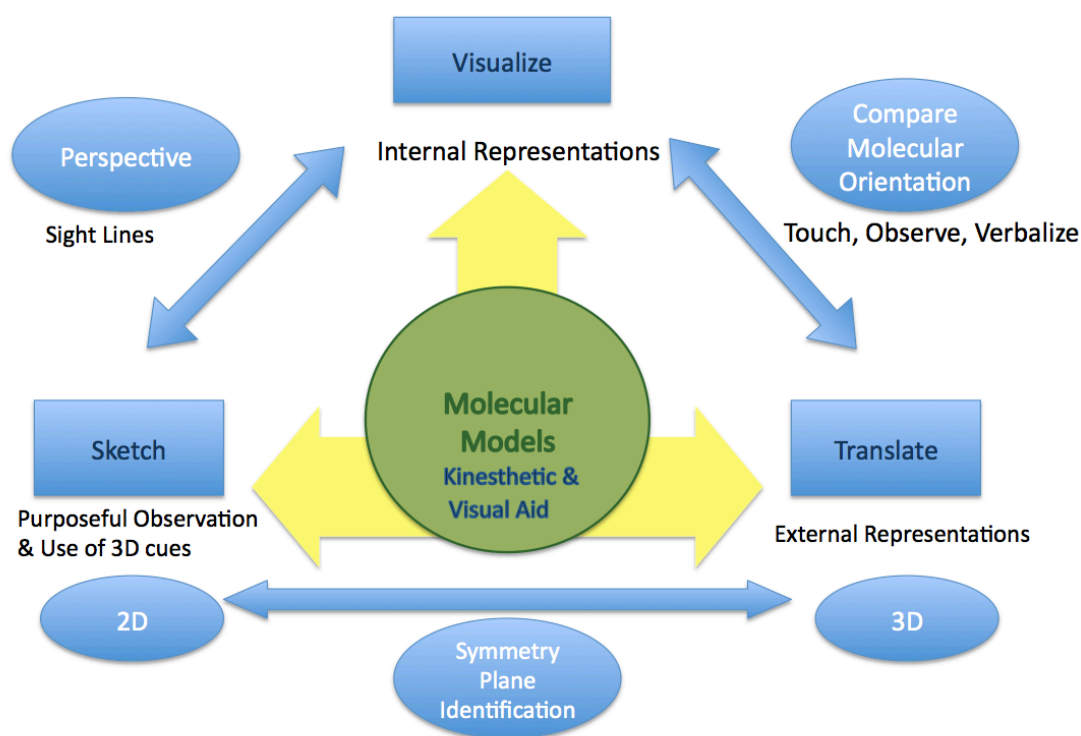


Figure 5.2 A Model for the Development of Chemistry Students Spatial Skills

These three skill areas were previously identified during the pilot study (Carlisle, 2012) and further explored through the literature in two areas; one regarding spatial skill within the discipline of chemistry and the other regarding the cognitive psychology of spatial skills. (Refer to the literature review for the development of these influential areas.)

However, the relationship between these skills and the facilitation necessary to develop

each one was further clarified and strengthened by this study, allowing for a deeper understanding of the cognitive processes students use to move between these areas. A triangle relationship similar to Johnstone's Model, as depicted in Figure 2.2 on page 26, seemed an appropriate way to represent the relationship between the different components of the model, and will be described in detail below. This model intentionally preserved simplicity by focusing on only the relationship between these three primary skill areas. *As is true in the training of any skill, it is key to address only the fundamental aspects, grounding experiences and learning in these areas first, prior to adding any layers of complexity.* Much like musicians learn scale and pitch, while artists learn colors and brush strokes; good teachers know how to orchestrate this balance of core skills prior to adding layers of complexity or difficulty. For the learning of spatial skills, this is of critical importance because spatial understanding has been shown to cause anxiety and cognitive overload (Ramirez et al., 2012; Newcombe & Stieff, 2012; Turner & Lindsay, 2003).

Currently, there is no model for the development of spatial skills by general chemistry students and this model may be helpful to instructors considering ways to integrate the learning of spatial skills into their curriculum, as this model provides a mechanism for understanding the process of skill development. As I will describe in detail below, using this model is like using an inquiry cycle. At the beginning spatial learning needs to be guided to scaffold the process for students in a manner similar to that required for learning to use an inquiry process. Over time as students become "skilled" developing the procedural knowledge necessary to reason with spatial information, they may not depend on molecular models as much for simple molecular structures, and the

facilitation areas, shown in ovals, would become internalized. An explanation of how to use the model, which was developed through an understanding of how students in this study acquired their spatial skills, will be described below.

Navigating through the Model

a. Sketch: Making a 3D Representation

Molecular models were sketched in each of the interventions. During intervention one, students spent most of their time in the bottom left area of this triangle, labeled “Sketch”. Here students practiced perspective taking to develop an understanding of sight lines and view. To sketch requires students to critically observe shape, because they have to decide how to represent the 3D arrangement of the atoms on paper, which is 2D. Students practice this skill by making judgments about, which atoms are within the plane of the paper and which are in/out based on their perspective. This allows students to apply dash/wedge cues appropriately. Research shows that “representational competence” as discussed by Kozma and Russel (2006) is an important step for students becoming chemists (Bodner, 1997; Wu & Shah, 2004).

b. Translate: Interpreting External Representations

During Interventions 2 and 3 students spent most of their time working back and forth in the bottom area of the triangle, between the right rectangle of “Translate” and the left rectangle of “Sketch.” Here students look at 3D molecular models and make direct associations from the atom positioning as seen, to a 2D sketch with dash/wedge cues. This step helps students to develop a spatial interpretation of a 2D representation. In this

stage the skills of sketching and translating build and support one another. The identification of a symmetry plane on a molecular model facilitates the translation between 3D and 2D. Symmetry plane identification allows students to determine which atoms are within a plane, based on the perceived orientation, and this allows them to determine which atoms are positioned in or out for proper use of dash/wedge cues. Molecular models were used continuously by students to reference geometric shape and symmetry plane location, which informed their interpretation of 2D information. Research shows that students need to be able to work effectively between different external representations. (Harle & Towns, 2011; Hegarty, 2012; Mohler, 2008)

c. Molecular Models

Molecular models mediated the skills between all areas of the triangle, and thus were placed in the middle. Molecular models were used to help students gain an appreciation for how atoms are spatially arranged in a molecule. Looking at a physical model allows students to become familiar with the geometric shapes of common molecules, and for some it refreshes their understanding of these common shapes. The kinesthetic aspects of touching and manipulating molecular models were shown to be important for 3D understanding, thus contributing to the accurate encoding of geometric shapes (Ericsson & Kintsch, 1995; Ferguson et al., 2008; Wesson, 2012). In this way, the data suggest that physical molecular models assist in visual and tactile encoding, both of which assist in the construction of mental imagery. Further, these experiences have been shown to more accurately construct mental imagery (Ramadas, 2009). Research has also shown that one's inability to use mental imagery and sketch limits their spatial reasoning

ability (Harle & Towns, 2011; Wu & Shah, 2004; Gabel and Sherwood, 1984), and as such are important areas to develop.

d. Visualize: Constructing Internal Representations

In all three interventions students were building internal representations of 3D molecules. Some shapes were familiar and some were new, introducing different spatial features, such as a four-carbon chain. Visualize is placed at the top of the triangle, because students are learning to create and use internal representations building memory stores with which to make future associations. This area is also placed at the top, because it is the more advanced end goal of spatial reasoning. This area is slowly developed through the other two areas, sketch and translate. Moving up from sketching to visualize, the ability to visualize and create mental images is facilitated by perspective taking. Through the experience of viewing molecular models from different sight lines students' awareness of 3D shape is developed, thus helping them to visualize. Over time, students develop the necessary internal representations for basic molecular structures, now they can reason with spatial information by making the necessary associations. Research shows that to meet the particular demands for working memory in a given skilled activity, students must acquire encoding methods and retrieval structures that allow efficient storage and retrieval from long term memory (LTM), (Ericsson & Kintsch, 1995). Visuospatial working memory (VSWM) is greatly influenced by LTM associations from perceptual experiences (Logie & Della Salla, 2005). This initial understanding of perceptual information leads to the more abstract reasoning processes required.

In this model, the navigation from one area to another is deliberately scaffolded through the facilitation areas, shown in ovals, which assist movement between the three skill areas. Importantly as mentioned, the molecular models are used to bridge all areas. Once mental imagery is developed for simple tasks students may not rely on molecular models as much as before. However, continuous model use will support them until a level of expertise is reached, which provides them with a stronger ability to visualize and use internal representations. Eventually, students may become experts, with the ability to reason easily with abstract spatial information. Research shows that experts have also developed analytic strategies that augment their ability to visualize (Cohen & Hegarty, 2007; Stieff, 2010; Wu & Shah, 2004). This model also incorporates analytic strategies, such as symmetry plane identification, and heuristics for efficient molecular comparisons strategies through the use of molecular models to teach skills such as perspective taking.

6. Additional Findings

Besides the findings discussed above this study also revealed a few other findings that contribute in a meaningful way to the research question. First, some interview results suggest that students tend to think about geometric structures by reasoning with Lewis Structure⁹ information, because it is the most commonly represented form of molecular structure. Lewis structures are flat showing only the connectivity of atoms and they generally do not provide information about spatial arrangement, see Figure 4.12 page 92. For students, Lewis structures are perhaps the most familiar way of representing a molecular structure, because they are the most common way of showing molecular

⁹ Lewis dot structures are representations that show the bonding between atoms of a molecule as well as the lone pairs of electrons that are present on atoms in a molecule.

structures during instruction, so perhaps it should not be surprising that students' think molecules "look" like the Lewis structures. This finding re-emphasizes how hard it is to shake a misconception once it has started to form. It also emphasizes the need to assist students in the interpretation of molecular shapes (Harle & Towns, 2011; Schwartz & Heiser, 2006) and re-emphasize the meaning of models. Perhaps because novice students are concrete thinkers they tend to neglect the theoretical limitations of models, which underscores the need to emphasize these during instruction (Wu, Krajack & Soloway, 2001). Even after the interventions and a full year of general chemistry four of eight students interviewed did not consider the 3D geometry of the molecule when shown a Lewis structure. Of note is that dash/wedge cues are frequently not used with Lewis structures. The reason this was so surprising was that these students had learned about VSEPR Theory¹⁰ in the previous fall and were conceptually expected to look at the Lewis structure and "think" tetrahedral geometry, because of four bonds to the central atom and no lone pairs. The idea of the tetrahedral geometry is foundational in introductory chemistry, yet during interviews half of the students looked at the Lewis structure and thought the spatial relationship of the atoms was flat. This data supports the idea that spatial reasoning skills require further development to ensure that students make the appropriate associations between 2D Lewis structures and the 3D geometries allowing them to successfully determine whether or not a molecule is polar. An understanding of polarity will help students predict a molecule's reactivity and thus how it will interact with other molecules. This understanding will assist them in reasoning about

¹⁰ VSEPR (Valence Shell Electron Pair Repulsion) Theory is used to describe and explain common 3D geometries in chemistry.

intermolecular forces in general chemistry, which play an important role in many conceptual areas such as thermochemistry, solid state, phase changes, and kinetics.

a. Identified Misconceptions

Two other misconceptions were also identified: Students believed that (1) polarity changes depending upon one's view of a molecular model, and (2) molecules are static. Being aware of these will be helpful when thinking about instruction in these areas. The first misconception underscores the need for students to view three-dimensional structures, while they are learning about this concept. Through the consideration of both Lewis structure *AND* molecular models students will be able to better apply electronegativity¹¹ and symmetry concepts, which will allow them to develop a much better understanding of the true nature of polarity. This research has shown that students require the development of translational skills to use both a representation and a model together effectively. Considering molecular movement makes spatial information more relevant and may result in changing the second misconception. Interview and field note comments suggest that students do not think molecules move or perhaps they simply do not consider molecular movement while reasoning, because mental rotation is already a difficult concept to grasp. Additional movement of the molecule may interfere with mental rotation increasing the complexity. Teaching about molecules using chemical formula symbols and Lewis Structures promotes the perception of static molecules. Teaching about spatial properties, which allow students the opportunity to raise questions about positioning of atoms within a molecule will promote a deeper understanding of what a chemical structure actually represents. This type of thinking could be introduced

¹¹ Electronegativity is a measure of an atoms ability to attract electrons toward itself in a chemical bond.

in the second semester during units for intermolecular forces, kinetics, and various areas of solution chemistry. Developing spatial knowledge will allow students to ask better questions. It is possible that these two misconceptions, polarity changing with view and molecules are static, are related because of students difficulty with mental rotations. Perhaps the reason some students think polarity changes with view is because they consider molecules to be oriented in one way. Drawing out students' misconceptions was another way that the intervention activities supported student learning.

D. Implications

This study has several implications for spatial skill development and it's instruction. First, this study shows that short (15-20 min.) repeated activities are effective for spatial training, therefore spatial training need not consume a large amount of class time to be effective. However, results do suggest that continuity over the semester may be an important feature. This study also shows that it is possible for a broad range of students to be trained together without the need to separate high and low ability, which is an important practical implication for large general chemistry courses. All students in this study participated in the intervention activities together and were not separated based on their spatial ability, as suggested by some previous studies (Turner & Lindsay, 2003; Sorby, 2009). Further, the qualitative findings and student participation support that the activities were helpful and interesting for all students, as there was little evidence of some students becoming bored or disinterested after starting the activities. Providing evidence that high spatial ability students did not require separate activities, and low ability students were not overwhelmed.

Recent research has shown that spatial training is an important factor contributing to persistence in early STEM course work (Uttal & Cohen, 2012). The activities in my study were advantageous to both genders, showing similar high scores of spatial ability for both females and males. Because females responded very well to a small amount of spatial training, increasing their practice with spatial reasoning by including similar activities in the general chemistry curriculum may help to maintain their interest in majoring in a STEM discipline.

While teaching students about concepts that require spatial visualization, the results of this study suggest that instructors should employ hand-held molecular models, even though computer generated images may be an easier way to present spatial concepts in the classroom. My results suggest that students' initial spatial understanding should be developed with hand-held molecular models, due to the benefit of haptic and visual sensory encoding. This study showed that students particularly appreciated the tactile aspects of molecular models:

*"It's easier to picture it rotating when you can put your hands on it."
"The physical model, because I can touch it with my hands and move it with my hands." (FN's, April 10, 2013)*

These comments are representative of a vast majority of students (68%) who wrote similar comments in their artifacts.

Class time should be devoted to practice with activities that enhance spatial skill. Students gained confidence and proficiency through the intervention activities. Importantly, the results suggest that training with hand-held models is needed for all students, even those with prior spatial knowledge, because applying spatial thinking to molecules may be a new and unique experience.

Instruction should allow opportunities for students to work in groups and verbalize to each other what they are “seeing” and thinking about. This study found that students benefitted from activities that required them to discuss spatial features of molecules, while viewing and manipulating a physical molecular model. These findings support research by Schwartz and Heiser (2003), which suggest students require perceptual experiences with a manipulative to scaffold their thinking, and that these experiences allow them to explain things, which would otherwise be hard to describe with language. The results of this study show that the time necessary for novices to scaffold their visualization with perceptual experiences, such that they no longer require a physical model, appears to be longer than one semester. Schwartz and Heiser (2003) state: “Educators often provide explanations of phenomena that students’ have not learned to perceive, and therefore, do not realize when they are missing something, (pg. 4).” My research shows that students required training with simple geometric shapes although they had already been exposed to these several times through out the year. Further, it was not obvious to students’ what spatial information was important to pay attention to and why. The guided activities developed for this study provided structure and focus to help students ascertain the necessary information, thus addressing the possibility that students do not know what information to attend to.

The Post-Test

The test developed for this study provides a first step toward developing a better understanding of student knowledge in the important area of spatial reasoning. Currently, there are no discipline specific tests to assess general chemistry students’ spatial knowledge. This test begins to address this important area through the development of

questions that require spatial information to clarify chemical properties related to relevant content areas. Although the post-test was designed to measure how students responded to the intervention activities that addressed skills required for organic chemistry, the test is certainly appropriate for assessing general chemistry students spatial skills. General chemistry teachers can use the test to assess whether a student developed understanding of three-dimensional structure as related to VSEPR Theory, intermolecular forces, symmetry and symmetry planes, structural comparisons, and the mental rotation of molecules.

E. Strengths and Limitations

1. Strengths

The current study has several strengths. In contrast to previously conducted spatial training studies it has a large control group drawn from a similar student population (Wai, et al., 2009); and has high internal validity because both the control and the experimental group had the same professor. The experimental group was a large and diverse student group; therefore the data should be representative of other student populations taking general chemistry leading to generalizable findings and good external validity. Furthermore, it seems students found the intervention activities useful because almost all student of the experimental group students (with the exception of 16) voluntarily participated in the activities with the majority participating in two and three interventions. No credit or other reward was offered for participation.

2. Limitations

Although this research offers some insight to assist in the development of students' spatial skills, there are a few limitations that are important to consider. First, the

fact that students could choose to participate throughout the course of the term also meant that there was at times inconsistent practice for students choosing to do only one or two activities, while the activities were designed to cumulatively strengthen student skills. Second, some areas of the post-test were developed by the researcher during this study and were not piloted prior to use, and thus some questions may not be internally consistent, and some questions may not be a valid measure for a given skill. Additionally, only two control group interviews were obtained, which made it hard to validate and draw conclusions for some areas of the qualitative data. Finally, individual student spatial skill gains were not measured, because many i-clicker numbers did not match between the pre and post-test participants and thus did not allow for a comparison of individual student performance over the course of the interventions.

F. Future Research

The results of this study suggest a number of future directions for research. In particular, future research should examine the performance of general chemistry students, who participated in the spatial interventions, after they transitioned into organic chemistry, to understand whether spatial skills were maintained and students could apply them to the new content. It would also be advisable to carry out a similar study again to obtain confirmatory data through replication of these results. In carrying out a study such as this for a second time, I feel it would be important to have several groups that consistently carry out the activities every three weeks and then to measure student pre/post gains.

For the purposes of student learning, it would be important to see if understanding and performance in conceptual areas such as VSEPR Theory, polarity, solid state,

solution chemistry, and intermolecular forces increases with the spatial training activities. For example, does student understanding of hydrogen bonding improve post training and relative to a control without training?

This research also makes available a pre and post-test as well as information that would help in the design of further test development as an assessment tool for general chemistry students spatial content knowledge.

Finally, future research should assess the model I developed for chemistry students' spatial development. To carry out this research it would be useful to have teachers implement the activities developed in this study, with fidelity to the guided group activities such that variation in student experiences are kept to a minimum. Some groups could start the interventions during VSEPR Theory in the fall while others start in the second semester to address the influence of content on development of spatial ability. Does spatial training allow students to better understand VSEPR Theory, and if so does this carry over to other areas that require this conceptual knowledge, or is it through the application of spatial information in areas such as intermolecular forces, covered spring term, that students' best learn it's value.

Each of the areas above are of interest as I continue to research and support how students' learn to reason with spatial information in chemistry. The implementation of these guided activities provides useful information that will serve to refine these existing activities, as well as to develop additional spatial curriculum for general chemistry.

APPENDIX A

PRE-TEST

APPENDIX B

POST-TEST

APPENDIX C

Test Item Analysis:

Table 2 Post-Test Questions (Item Analysis)

Question	Cognitive factor (comprising the construct of SA)	Spatial Skill Translating, sketching, visualizing- identified skills from pilot
1. Which of these molecules is polar?	VZ	Mental image, or memorization (Establish relevance of 3D to content- not skill...)
2. What is the maximum number of atoms that can lie w/in a symmetry plane?	VZ, SO	Identify symmetry plane Mental image or memorization Deconstruction of mental 3D image
3. Does fluoromethane, CH ₃ F, possess a plane of symmetry?	VZ, SO, SR	Identify symmetry plane Mental rotation of 3D image
4. When sighting down the C-C chain of pentane, C ₅ H ₁₂ , how does it look?	VZ, SO	Mental Image, or memorization Perspective taking
5. Does methanol, CH ₃ OH, possess a plane of symmetry?	VZ, SO	Identify symmetry plane, Mental image, or memorization
6. Which of these molecules is NOT flat? (VSEPR)	VZ	Mental image, or memorization (Establish relevance of 3D to content- not skill...)
7. Are these molecules the same?	SR, SO, VZ (maybe 3D dsh/wdg features)	Simple rotation, matching of molecular features, (mental rotation), perspective taking
8. Consider molecule (rendered in 3-D) C ₂ H ₅ NH ₂ what would it look like after a rotation about the Y-axis?	SO, SR, VZ	Mental rotation of 3D image, Perspective taking Molecular orientation
9. Consider molecule PCl ₄ I, (rendered image) how would this look when viewed from the	SO, SR, VZ	Mental rotation of 3D image, Perspective taking Molecular orientation

bottom (arrow points to spot)?		
10. How many water molecules could H-bond to 1 methanol molecule? (shown in 3D)	SO, VZ	Mental image (imagining interactions) Molecular orientation
11. Are these molecules the same?	SR, SO, VZ	Simple rotation, matching of molecular features, (mental rotation)
12. Which of these molecules are the same?	SR, SO, VZ (Not complex...)	Simple rotation, matching of molecular features, (mental rotation)
13. Which of these molecules are the same?	SR, SO, VZ	Mental rotation of 2D sketch (dash/wedge) both out of and w/in the plane.
14. Which of these sketches correctly represents the molecule, NH ₂ F as shown below?	VZ, SO	Translation of 3D molecular image to 2D sketch with dash/wedge. Sketching perspective
15. Which of these sketches correctly represents the molecule shown below when viewed down the F to C bond?	VZ, SO	Translation of 3D molecular image to 2D sketch with dash/wedge. Sketching perspective

The pre-test contained six questions from the PSVT developed by Bodner and Guay 1997 (Ref #superscript JCE), other **pre and post test items were developed by the researcher** (items were tied to specific cognitive factors for spatial reasoning skills – based on theory proposed by Lohman (ref) recognizing that spatial ability is a comprehensive construct – so that validity was established, items related to the construct of spatial ability were developed through pilot study, and scoring showed significant differences for these items) as done according to (Sages2 Examiner’s manual Ch.6 Prufrock Press ebook). The cognitive factors represent the 3 major factors generally recognized and accepted as common attributes for spatial ability, spatial relations(SR), spatial orientation(SO), and visualization(VZ).

APPENDIX D

INTERVENTION ONE

Appendix D

Intervention #1

Name: _____

PART I: Visualizing Molecules and Polarity

1. Construct a tetrahedron of dichloromethane, CH_2Cl_2 , out of the molecular models provided to your group.

a) How would your model look if you viewed it from the top? Make a sketch to support.

b) Chemists use dash/wedge notation to denote three-dimensional features of molecules in a 2-D sketch. The wedge represents an atom that is located out toward you (the viewer). The dash is used to represent an atom going back behind the plane of the paper, and away from the viewer (see CH_4 below for an example)

With your model sitting stationary on the bench top, view it from the right side, and then from the left side. What, if anything, changed? Use the dash/wedge notation to make a 3-D sketch from these two different perspectives (right/left).

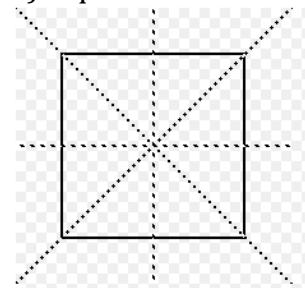
c) Is this molecule polar? Discuss with your group. Explain briefly why or why not using the 3-D sketch information above.

d) If you hold this molecule and rotate it to inspect it from different angles. What is the maximum number of atoms that can lie within a plane at any one time?

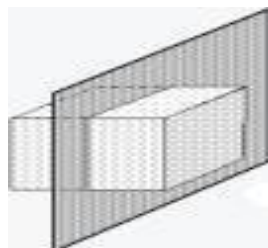
PART II: Symmetry

Symmetry is an important idea in nature and science. It is often useful because it allows us to consider the balance and “evenness” of a chemical structure. When you are considering compounds in 2-D as written or sketched on a piece of paper, a molecule would possess a **line of symmetry** if it could be bisected in such a way that there are two equal halves (see (A) below). This square shows four lines of symmetry. When considering a molecule or shape in 3-D it may possess a **plane of symmetry** if it can be bisected into equal halves in three dimensions (see (B) below). The darker gray shaded plane represents a plane of symmetry through the rectangular cube.

A) Square



B) Rectangular cube



2. In your groups **make a model of ethanol C_2H_5OH , and butane (C_4H_{10}) to share** while thinking about the following questions:

- Are these molecules symmetrical?
- Can you find a plane of symmetry for both molecules?
- How do you think symmetry affects polarity? Use your molecular models to help explain. You may make a sketch to support your answer

Appendix E

Group Activity #2

Name: _____

PART I: Sketching Molecules

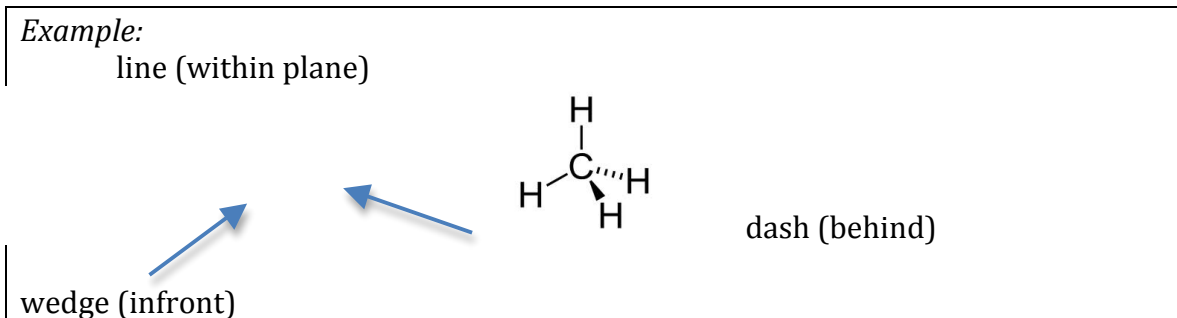
1. View the molecular models of nitrogen trifluoride, NF_3 and phosphorus pentafluoride, PF_5 .

a) Use your dot matrix paper to make a 3-D sketch of the models by following these steps.

Step 1: Hold each model, rotate it, and decide the maximum number of atoms that can lie within a plane. Discuss with your group members to reach a consensus. Draw the bonds to those atoms with a straight line indicating they are within the plane.

Step 2: Which atom(s) appears to be coming out toward you? Use a wedge to show this feature.

Step 3: Lastly, if there is any atom(s) going behind the reference plane use a dash (series of small dashes).



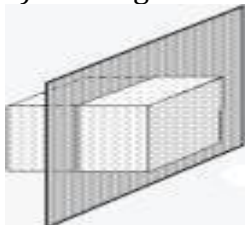
NF_3 Sketch

PF_5 Sketch

b) Are these molecules polar or non-polar? Label each with a P or NP.

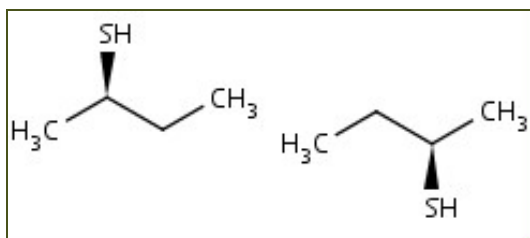
2. Recall that symmetry is an important idea in nature and science. It is often useful because it allows us to consider the balance and “evenness” of a chemical structure. When considering a molecule or shape in 3-D it may possess a **plane of symmetry** if it can be bisected into equal halves in three dimensions (see figure A below). The darker gray shaded plane represents a plane of symmetry through the rectangular cube.

A) Rectangular cube



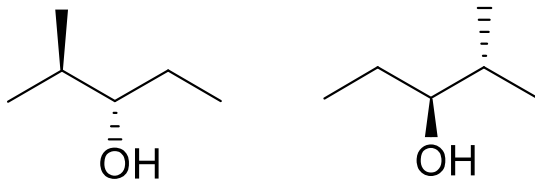
Identify 2 planes of symmetry for each of your molecules in part 1. Discuss with your partner or group, and sketch them in with pencil.

3. a) Using just the 2-D sketch below (i.e. no models) determine whether these molecules are the same. Briefly explain your reasoning.



3. b) Next, look carefully at the models of 2- butanethiol(*structure shown in 3a) above*) provided. Are they the same molecule? How can you tell? Briefly explain.

4. a) Using just the 2-D sketch below (i.e. no models) determine whether these molecules are the same. Briefly explain your reasoning.



4. b) Look carefully at the models of 2- methyl, 3-hydroxy pentane provided. Are they the same molecule? How can you tell? Briefly explain.

Appendix F

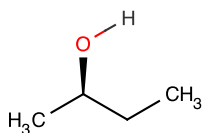
Activity #3B: Visualizing Molecular Orientations Name: _____

These questions will help you to visualize the 3-D relationships of molecules.

1. Look at the model of **2-butanol, C₄H₉OH**, with your partner.

a) Position it so that it looks like this sketch below. *Note that the carbon chain (carbon to carbon bonds make a zig-zag AND importantly that they lie along one plane). This feature is a helpful reference when you are sketching the structure.*

Notice also that some hydrogen atoms are not shown in the line sketch – locate them on the molecular model. It is assumed that hydrogen's are attached in these positions, because it is a well-known fact that carbon makes 4 bonds. Omitting the hydrogen's makes the molecule easier to sketch and it makes important features of the molecule more obvious when visualizing.



On the left you see a wedge attaching the OH group in 2-butanol. Recall that the wedge indicates coming out toward you (the viewer) and a dash means going back behind the plane of the paper, away from the viewer.

b) What happens to the hydroxyl group, OH when you rotate the molecule 180° to the right around the y-axis? Make a line sketch like the one above to show the new orientation of the molecule.

c) What happens to the hydroxyl group, OH when you rotate the molecule 180° to the left around the y-axis? Make a line sketch to show the new orientation of the molecule.

d) What happens to the hydroxyl group, OH when you rotate the molecule 180° around the x-axis? (*Hint: watch the carbon chain as you make the rotation so that you can easily tell when you have completed a 180° rotation.*) Make a line sketch to show the new orientation of the molecule.

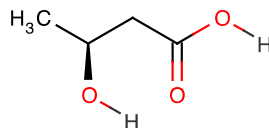
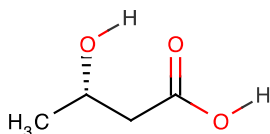
e) Does it matter which way you rotate the model about the x-axis?

2. Using the molecular models to assist you, consider how a molecule of ethanol, C_2H_5OH would interact with several water (H_2O), molecules in an aqueous solution.

a) Discuss this with your group and show each other where these attractive interactions would take place. Reach a consensus about how this might look if you visualized all of the hydrogen bonding interactions at once.

b) Now try to make a sketch that represents your thinking.

3. Lactic acid (2-hydroxypropanoic acid) is an acid found in milk, and it is also produced in our muscles during strenuous exercise such as sprinting. Are these molecules the same? Discuss your ideas with your group. Briefly explain and try to be specific.



OPTIONAL:

5. Look at the Spartan image of lactic acid on the computer screen, and compare it to the molecular model of lactic acid. Does the model or the computer image better assist you in your visualization process?

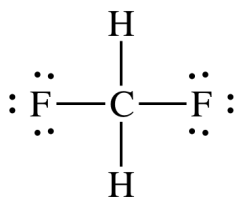
Appendix G Interview Questions

Chemistry 112
D. Carlisle

Interview Questions

Name:

1. a) Is a molecule of difluoromethane, CH_2F_2 polar ?



b) Next, look at the molecular model of CH_2F_2 provided and consider whether the molecule is polar or nonpolar. Explain your reasoning.

2. a) Write the Lewis structure for ethanol, $\text{C}_2\text{H}_5\text{OH}$. Is this a polar molecule?

b) Can you imagine two separate places on ethanol where water molecules could form a hydrogen bond? If so sketch them into your Lewis Structure above.

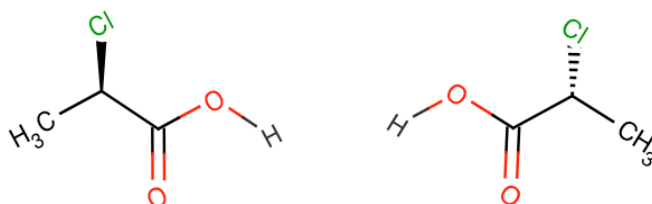
c) Next, while referring to the molecular model of ethanol provided, make a 3-D sketch using dash/wedge notation.

d) Does this molecule possess a plane of symmetry? Explain.

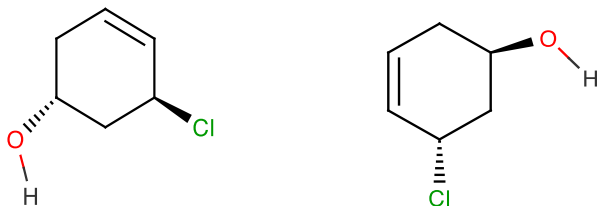
3. While holding a molecular model of carbon tetrachloride, CCl_4 , determine the maximum number of atoms that could lie with in a symmetry plane.

4. Using the models provided, describe how three molecules of ethanol, $\text{C}_2\text{H}_5\text{OH}$ might attract one another, when forming intermolecular attractions? Specifically explain the orientation of the molecules with respect to one another.

5. Compare the two structures of 2-chloro-propanoic acid shown below. Are they the same? Explain the process you use to determine whether or not they are the same molecule. *For example, in which direction and how, would you mentally rotate them as you compare the structures.*



6. a) Compare the two cyclic structures of shown below. Are they the same? *Explain the process you use to determine whether or not they are the same molecule.*



b) Compare the two molecular models of the two molecules above in part a) **provided for you**. How do these structures compare? *Explain your reasoning*.

7. Which aspect of this course, Chemistry 112, provides the most useful practice with conceptual information?

- a) lecture b) OWL homework c) studying with peers
d) studying on your own e) laboratory experiments

8. In your opinion the most useful learning opportunities take place while

- a) reading the text b) participating in class lecture c) doing OWL homework
d) studying outside of class e) laboratory experiments

9. In general, do you feel that the spatial activities helped you to think about molecules in three-dimensions?

- a) never b) rarely c) once in a while d) often

10. What is your major? _____

Informed Consent

My name is Deborah Carlisle and I am a doctoral candidate at the University of Massachusetts, Amherst in the Teacher Education and Curriculum Studies concentration. For my dissertation research I am concentrating on spatial reasoning in undergraduate chemistry. The aim of this research is to provide support that improves student learning and acquisition of these important skills. Additionally, this research will provide further insight for establishing best practices that foster student learning of spatial skills.

I am inviting you to participate in my research.

By participating in my study you will have the opportunity to improve your spatial reasoning skills, strengthening your ability to work with molecules in 3-D.

As a participant you will agree to:

- a. Answer some questions about your learning, and understanding of general chemistry concepts related to spatial reasoning
- b. Work on 5 small group activities during your lab sections for 10-15min.

The information gathered through observations and conversations, during these sessions, will be shared with other science researchers and educators. All information gathered will be anonymous, and I will not share individual names of participants to protect your confidentiality.

Your participation is voluntary and you are free to discontinue or refuse participation at any time without penalty or prejudice. You also have the right to review any of the materials used in this study and a summary of the results will be made available upon request.

You have been provided with two copies of this informed consent, both which should be signed if you are willing to participate. One copy should be retained for your records and the other form is for my records. Your signature below indicates that you:

- a. Have read and understand the information provided
- b. Willingly agree to participate
- c. May withdraw your consent at any time.

If you have any questions about this research or your participation in it, you can reach me at:

Deborah Carlisle
413-259-5736
dcarlisle@educ.umass.edu

You may also contact:

Linda Griffin
Associate Dean for Academic Affairs
lgriffin@educ.umass.edu

You may also contact:

Professor Kathleen Davis, and Professor Martina Nieswandt
Dept of Teacher Education and Curriculum Studies
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Email: kdavis@educ.umass.edu, mnieswan@educ.umass.edu

Signature: _____ Date: _____

REFERENCES

- Bodner, G. & Guay, R. (1997). The Purdue visualization of Rotations Test, *The Chemical Educator*, 2(4), 12 - 37.
- Bodner, G. & Orgill, M. (2007). *Theoretical Frameworks for Research in Chemistry/Science Education*. Pearson, Prentice Hall, Upper Saddle River NJ.
- Brooks J. & Brooks, M. (1999). *In Search of Understanding – The Case for Constructivist Classrooms*. Alexandria VA, ASCD.
- Carlisle, D. (2012). Spatial Reasoning in Organic Chemistry: From Novice to Expert the Missing Links. *Science Education*, In Preparation.
- Carroll, J. (1993). *Human Cognitive Abilities: A survey of factor-analytic studies*. Cambridge University Press, Cambridge England, 304 - 363.
- Coffey, A. & Atkinson, P. (1996). *Making Sense of Qualitative Data*. Thousand Oaks, CA: Sage Publications.
- Cohen, C. & Hegarty, M. (2007). Individual Differences in Use of External Visualisations to Perform an Internal Visualisation Task. *Applied Cognitive Psychology*, 21, 701-711.
- Coleman, S. & Gotch, A. (1998). Spatial Perception Skills of Chemistry Students. *Journal of Chemical Education*, 75(2), 206-209.
- Contreras, J., Colom, R., Hernandez, J., & Santacreu, J. (2003). Is Static Spatial Performance Distinguishable from Dynamic Spatial Performance? A Latent-Variable Analysis, *The Journal of General Psychology*, 130(3), 277-288.
- Creswell, J. & Plano Clark, V. (2011). *Designing and Conducting Mixed Methods Research*. Sage, Washington, D.C.
- Davidowitz, B. & Rollnick, M. (2011). What Lies at the Heart of Good Undergraduate Teaching? A Case Study in Organic Chemistry. *Chemical Education Research and Practice*, 12, 355-366.
- Ehrlich, S., Levine, S. & Goldin-Meadow. (2006). The Importance of Gesture in Children's Spatial Reasoning. *Developmental Psychology*, 42(6), 1259-1268.
- Ericsson, K. Kintsch, W. (1995). Long-Term Working Memory Performance. *Psychological Review*, 102(2), 211-245.
- Eysenk, M. & Keane, M. (2010). *Cognitive Psychology: A students handbook*. Psychology Press, N.Y.

- Ferguson, C., Ball, A. McDaniel, W. & Anderson, R. (2008). A Comparison of Instructional Methods for Improving the Spatial Visualization Ability of Freshman Technology Seminar Students. IAJC-IJME International Conference. ISBN 978-1-60643-379-9.
- Gabel, D. & Sherwood, R. (1984). Problem Solving Skills of High School Chemistry Students. *Journal of Research in Science Teaching*, 28(6), 505-521.
- Gall, M. Gall, J & W. Borg. (2005). *Educational Research, An Introduction*, Allyn and Bacon, N.Y.
- Gilbert, J. (2005). Visualization: A Metacognitive Skill in Science and Science Education. In J.K. Gilbert (Ed.), *Visualization in Science Education* (pp. 9-27). Netherlands, Springer.
- Harle, M. & Towns, M. (2011). A Review of Spatial Ability Literature, it's Connection to Chemistry, and Implications for Instruction. *Journal of Chemical Education*, 88(3), 351-360.
- Healey, K., Hasher, L. & Danilova, E. (2011). The Stability of Working Memory: Do Previous Tasks Influence Complex Span? *Journal of Experimental Psychology: General*, 140(4), 573-585.
- Hmelo-Silver, C. & Pfeffer, M. (2004) Comparing Expert and Novice Understanding of a Complex System from the Perspective of Structures, Behaviors, and Functions. *Cognitive Sciences*, 28, 127-138.
- Hegarty, M. (2012). Meta-Representational Competence as an Aspect of Spatial Intelligence. *Cognitive Sciences*, 1240-1241.
- Herron, D. & Nurrenbern, S. (1999). Chemical education research: Improving Chemistry Learning. *Journal of Chemical Education*, 76(10), 1353-1361.
- Johnstone, A. (2000). Chemical Education Research: Where from Here? *University Chemistry Education*, 4(1), 34-39.
- Kozma, R. & Russel J. (2006). Students becoming chemists: Developing Representational Competence. In J.K. Gilbert (Ed.), *Visualization in Science Education* (pp. 121-146). Netherlands, Springer.
- Logie, R., Della Salla, S., Beschin, N. & Denis, M. (2005). Dissociating mental transformations and visuo-spatial storage in working Memory: Evidence from representational neglect. *Memory*, 13(3/4), 430-434.

- Lohman, D. (1979). Spatial Ability: A Review and Reanalysis of the Correlational Literature. Technical Report No. 8, Aptitude Research Project. Sanford University, Palo Alto CA.
- Mohler, J. (2008). The Impact of Visualization Methodology on Spatial Problem Solutions Among High and Low Visual Achievers, *Journal of Industrial Technology*, 24(1), 2-9.
- National Science Board (2010). Preparing the Next Generation of STEM Innovators: Identifying and Developing our Nation's Human Capital. NSB-10-33.
- Newcombe, N. & Steiff, M. (2012). Six Myths About Spatial Thinking. *International Journal of Science Education*, 34(6), 955-971.
- Presidents Council of Advisors on Science and Technology, (2010). Report to the President. Prepare and Inspire: K-12 Education in Science, Technology, Engineering and Math (STEM) for America's Future.
- Ramadas, J. (2009). Visual and Spatial Modes in Science Learning. *International Journal of Science Education*, 31(3), 301-318.
- Ramirez, G., Gunderson, E., Levine, S., & Beilock, S. (2012). Spatial Anxiety Relates to Spatial Abilities as a Function of Working Memory in Children. *The Quarterly Journal of Experimental Psychology*, Psychology Press, 1-14.
- Rossman, G. & Rallis, G., (2012). *Learning in the Field*. (3rd Ed.) Sage Publications: Thousand Oaks, CA.
- Schwartz, D. & Heiser, J. (2003). Spatial Representations and Imagery in Learning. *Journal of Learning Sciences*. K. Sawyer (Ed.) Cambridge University Press.
- Smith, J., diSessa, A., Roschelle, J. (1993). Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition. *Journal of Learning Sciences*, 3(2), 115-163.
- Sorby, S. (2009). Educational Research in Developing 3-D Spatial Skills for Engineering Students. *International Journal of Science Education*, 31(3), 459-480.
- Stieff, M. (2007). Mental Rotation and Diagrammatic Reasoning in Science. *Learning and Instruction*, 17(2), 219-234.
- Stieff, M. (2010). When is a molecule three dimensional? A task-specific role for imagistic reasoning in advanced chemistry. In Ford, M. and Varelas, M. (Eds.), *Learning and Science Education* (pp.310-336). Wiley Periodicals.

- Stieff, M., Bateman, R. & Uttal, D. (2005). Teaching and learning with three dimensional representations. In J.K. Gilbert (Ed.), *Visualization in Science Education* (pp. 93-118). Netherlands, Springer.
- Stieff, M., Ryu, M., Dixon, B. & Hegarty, M. (2012). The Role of Spatial Ability and Strategy Preference for Spatial Problem Solving in Organic Chemistry. *Journal of Chemical Education*, 89, 854-859.
- Strauss, A. and Corbin, J. (1998). *Basics of Qualitative Research* (2nd Ed.) Sage Publications: Thousand Oaks, CA.
- Taagerpera, M., Arasasingham, R. & King, S. (2011). Integrating symmetry in stereochemical analysis in introductory organic chemistry. *Chemical Education Research and Practice*, 12, 322-330.
- Taagerpera, M. & Noori, S. (2000). Mapping Students' Thinking Patterns in Learning Organic Chemistry by the Use of Knowledge Space Theory. *Journal of Chemical Education*, 77(9), 1224-1229.
- Terlecki, M., Newcome, N., & Little, M. (2008). Durable and Generalized Effects of Spatial Experience on Mental Rotation: Gender Differences in Growth Patterns. *Applied Cognitive Psychology*, 22, 996-1013.
- Tseng, T. (2009). Spatial-Visual Skills and Engineering Design. MIT.
- Turner, R. & Lindsay, H. (2003). Gender differences in Cognitive and Noncognitive factors related to achievement in Organic Chemistry. *Journal of Chemical Education*, 80(5), 563-568.
- Uttal, D. & Cohen, C. (2012). Spatial Thinking and STEM Education: When, Why, and How? *Psychology of Learning and Motivation*, 57, 147- 178.
- Wai, J., Lubinski, D., & Benbow, C. (2009). Spatial Ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101(4), 817-835.
- Wallentin, M., Kristensen, L., Olsen, J., & Nielsen, A. (2011). Eye Movement Suppression Interferes with Construction of Object-Centered Spatial Reference Frames in Working Memory. *Brain and Cognition*, 77, 432-437.
- Weckbacher, L.M. & Okamoto, Y. (2012). Spatial Ability Among High Academic Achievers, *Journal for the Education of the Gifted*, 35(1), 49-65.

- Wesson, K. (2012). Brain-sight: Can touch allow us to “see” better than sight? BrainWorld magazine, online url: <http://brainworldmagazine.com/brain-sight-can-touch-allow-us-to-see-better-than-sight/>
- Wu, H., Krajcik, J., & Soloway, E. (2001). Promoting Understanding of Chemical Representations: Students’ Use of a Visualization Tool in the Classroom. *Journal of Research in Science Teaching*. 38(7), 821-842.
- Wu H. & Shah P. (2004). Exploring Visuospatial Thinking in Chemistry Learning. *Science Education*. 88(3), 465- 492.
- Yilmaz, H. B., (2009). On the development and measurement of spatial ability. *International Electronic Journal of Elementary Education*, 1(2), 83-96.