Visualizing the Invisible: Generating Explanations of Scientific Phenomena

Eliza Bobek

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy under the Executive Committee of the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2012
ABSTRACT

Visualizing the Invisible: Generating Explanations of Scientific Phenomena

Eliza Bobek

Many topics in science are notoriously difficult for students to learn. Mechanisms and processes that exist on a scale outside student experience present particular challenges. While instruction often involves visualizations, students typically explain in words, spoken or written. Visualizations have many advantages over verbal explanations, especially for science, so asking students to produce visual rather than verbal explanations should improve their learning. This hypothesis was tested in two domains, a mechanical system and a chemical system. The explanations were analyzed for content, and learning assessed by a post-test. Participants’ spatial ability was also assessed as spatial ability often correlates with learning science.

For the verbal explaining of a mechanical system, the bicycle tire pump, high spatial participants performed better than low spatial participants. However, low spatial participants performed better and as well as high spatial participants after producing visual explanations. Visual explanations included significantly greater amounts of structural information, as well as other features essential to understanding function, for example a complete explanation of the inlet valve, a crucial but invisible structural component.

In the domain of chemical bonding, visual explanations were more effective than verbal explanations, and high spatial ability participants showed greater learning than low spatial ability participants. Visual explanations contained a significantly greater amount of structural information, made reference to specific examples of chemical compounds, and often contained supplementary text. Text added to visual explanations predicted post-test scores, as did the inclusion of invisible features. Many participants who drew identified actual examples of ionic
and covalent molecules. Written explanations often used general terms and presentations of
definitions. Explanations generated by high spatial ability participants contained greater amounts
of function and were more likely to include specific examples.

In both domains, text was often spontaneously added to visual explanations. In
Experiment 1, added text was equally likely to describe structure or function; in Experiment 2,
added text was more likely to describe function. Taken together, the studies provide support for
the use of learner-generated visual explanations as a powerful learning tool and suggest that
visual explanations are superior because they demand and provide a check for completeness of
explanations.
TABLE OF CONTENTS

LIST OF TABLES  iii

LIST OF FIGURES  iv

1. INTRODUCTION  1

2. LITERATURE REVIEW  4

2.1 Difficulties in Learning Invisible Processes in Science  4
2.2 Learning from Representations in Science  6
2.3 Learner-generated Explanations  9
2.4 Learner-generated Explanations in Visual and Verbal Formats  11
2.5 The Role of Spatial Ability in Learner-generated Explanations  16
2.6 Summary  18

3. EXPLAINING THE FUNCTION OF A MECHANICAL SYSTEM: THE BICYCLE TIRE PUMP  19

3.1 Introduction  19
3.2 Method  19
3.2.1 Participants  20
3.2.2 Design  20
3.2.3 Materials  20
3.2.4 Procedure  22
3.3 Coding  24
3.3.1 Coding System for Structure and Function  24
3.3.2 Coding of Essential Features  26
3.3.3 Coding of Invisible Features  29
3.3.4 Coding Visual Elements: Arrows and Multiple Steps  30
3.4 Results  31
3.4.1 Spatial Ability  31
3.4.2 Structure and Function  32
3.4.3 Essential Features  34
3.4.4 Invisible Features  35
3.4.5 Arrows  36
3.4.6 Multiple Steps  37
3.4.7 Learning Outcomes  38
3.5 Discussion  40
4. EXPLAINING A SUBMICROSCOPIC PROCESS: CHEMICAL BONDING

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>43</td>
</tr>
<tr>
<td>4.2</td>
<td>Methods</td>
<td>44</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Participants</td>
<td>44</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Design</td>
<td>44</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Materials</td>
<td>45</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Procedure</td>
<td>46</td>
</tr>
<tr>
<td>4.3</td>
<td>Coding</td>
<td>48</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Coding System for Structure and Function</td>
<td>48</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Coding System for Arrows</td>
<td>52</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Coding for the Use of Specific Examples</td>
<td>53</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Coding for the Use of Multiple Representations</td>
<td>56</td>
</tr>
<tr>
<td>4.4</td>
<td>Results</td>
<td>57</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Spatial Ability</td>
<td>57</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Structure and Function</td>
<td>57</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Arrows</td>
<td>60</td>
</tr>
<tr>
<td>4.4.4</td>
<td>Use of Specific Examples</td>
<td>61</td>
</tr>
<tr>
<td>4.4.5</td>
<td>Use of Multiple Representations</td>
<td>62</td>
</tr>
<tr>
<td>4.4.6</td>
<td>Learning Outcomes</td>
<td>62</td>
</tr>
<tr>
<td>4.5</td>
<td>Discussion</td>
<td>65</td>
</tr>
</tbody>
</table>

5. DISCUSSION

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>67</td>
</tr>
<tr>
<td>5.2</td>
<td>Summary of Significant Findings</td>
<td>67</td>
</tr>
<tr>
<td>5.3</td>
<td>Role of Spatial Ability</td>
<td>69</td>
</tr>
<tr>
<td>5.4</td>
<td>Benefits of Learner-generated Explanations</td>
<td>71</td>
</tr>
<tr>
<td>5.5</td>
<td>Benefits of Learner-generated Visual Explanations</td>
<td>72</td>
</tr>
<tr>
<td>5.6</td>
<td>Limitations of the Experiments</td>
<td>76</td>
</tr>
<tr>
<td>5.7</td>
<td>Future Studies</td>
<td>78</td>
</tr>
<tr>
<td>5.8</td>
<td>Conclusion</td>
<td>80</td>
</tr>
</tbody>
</table>

REFERENCES

APPENDICES

Appendix A: Post-tests
Appendix B: Vandenberg-Kuse Mental Rotation Test
LIST OF TABLES

Table 3-1. Coding guide for structure. 25

Table 3-2. Coding guide for function. 25

Table 3-3. Number of structural and functional units in visual and verbal explanations of the bicycle pump. 32

Table 4-1. Coding guide for structure. 49

Table 4-2. Coding guide for function. 50

Table 4-3. Number of structural and function units in visual and verbal explanations of bonding. 57
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Examples of visual explanations.</td>
<td>26</td>
</tr>
<tr>
<td>3-2</td>
<td>Example of visual explanation showing a tight seal between the piston and the chamber.</td>
<td>27</td>
</tr>
<tr>
<td>3-3</td>
<td>Example of verbal explanation coded for the maximum of four points for essential features.</td>
<td>28</td>
</tr>
<tr>
<td>3-4</td>
<td>Example of verbal explanation describing invisible features.</td>
<td>29</td>
</tr>
<tr>
<td>3-5</td>
<td>Example of visual explanation depicting multiple steps.</td>
<td>30</td>
</tr>
<tr>
<td>3-6</td>
<td>Example of visual explanation featuring multiple perspectives.</td>
<td>31</td>
</tr>
<tr>
<td>3-7</td>
<td>Number of structural and functional units in visual and verbal explanations of the bicycle pump.</td>
<td>33</td>
</tr>
<tr>
<td>3-8</td>
<td>Number of structural and functional units contained in words and pictures.</td>
<td>34</td>
</tr>
<tr>
<td>3-9</td>
<td>Scores for essential features in visual and verbal explanations.</td>
<td>35</td>
</tr>
<tr>
<td>3-10</td>
<td>Scores for the inlet valve in visual and verbal explanations.</td>
<td>36</td>
</tr>
<tr>
<td>3-11</td>
<td>Scores for arrows used in visual explanations.</td>
<td>37</td>
</tr>
<tr>
<td>3-12</td>
<td>Scores on post-test for explanations containing a single step and multiple steps.</td>
<td>38</td>
</tr>
<tr>
<td>3-13</td>
<td>Scores on the post-test, by group and spatial ability.</td>
<td>39</td>
</tr>
<tr>
<td>3-14</td>
<td>Scores on functional questions on the post-test, by group and spatial ability.</td>
<td>39</td>
</tr>
<tr>
<td>4-1</td>
<td>Visual explanation of chemical bonding.</td>
<td>51</td>
</tr>
<tr>
<td>4-2</td>
<td>Verbal explanation of chemical bonding.</td>
<td>52</td>
</tr>
</tbody>
</table>
Figure 4-3. Example of visual explanation showing the use of arrows.  

Figure 4-4. Example of visual explanation showing the use of specific examples.  

Figure 4-5. Example of explanation showing the use of multiple representations.  

Figure 4-6. Example of “creative” visual explanation.  

Figure 4-7. Number of structural and functional units in visual and verbal explanations of chemical bonding.  

Figure 4-8. Structural and functional information in pictures and words contained in visual explanations.  

Figure 4-9. Number of structural and functional units generated by low and high spatial participants for both visual and verbal explanations.  

Figure 4-10. Mean number of arrows used to label and show movement.  

Figure 4-11. Scores on the delayed post-test, by group and spatial ability.  

Figure 4-12. Scores on the delayed post-test, by group.  

Figure 4-13. Scores on the delayed post-test, by spatial ability.
ACKNOWLEDGEMENTS

There are many people I wish to thank for their contributions to this dissertation. First, I want to thank Barbara Tversky for her constant guidance, support, and encouragement. I would also like to thank James Corter for his advisement throughout my time in graduate school. O. Roger Anderson was invaluable as the Chair of my dissertation committee. In addition, I wish to thank Stephen Peverly and Lisa Son for their important feedback and insight.

Additionally, I want to express my gratitude to all of my friends, especially to my Barnard girls, who gave me the confidence and encouragement I needed to finish this project. I also need to thank my sister Molly for her love, support, and hours of both editing and babysitting, and my husband, Daniel, for his love and constant faith in me. Finally, this work is dedicated to my daughter, Lucia, whose love, laughter and joy inspire me every day.
CHAPTER 1
INTRODUCTION

The physical world that we can see and touch is in fact very limited. We must often attempt, therefore, to make sense of the invisible and the untouchable. Many processes in science are often invisible or contain hidden mechanisms that cannot be directly observed. These phenomena, such as gravitational pull, chemical bonding, cellular processes, and evolution, are inherently invisible or exist at scales of size and complexity that are beyond observation. When students attempt to learn these phenomena, they often experience difficulty because they must understand not only the individual components of the processes (structure) but also the interactions and mechanisms (function). If the phenomena are macroscopic, sub-microscopic, or abstract, there is an additional level of difficulty.

Teaching invisible processes to students often involves providing them with various types of visual information, including illustrations, diagrams, animations, and interactive simulations that explain the concepts (e.g. Hegarty & Just, 1993; Hegarty, Kriz, & Cate, 2003; Mayer et al., 2005). Although many types of visualizations are constructed with the use of technology, drawings, diagrams, and graphs have long been constructed manually and have been used to represent and communicate knowledge. There are many advantages to learning with these types of external visualizations. Diagrams use elements and space to represent elements and their spatial relations literally or metaphorically, and these relations can be directly perceived (Tversky, 2002; 2011). Pictorial elements are used to express time, number, and size, and can also schematize and distort to convey meaning. External visualizations off-load memory, encourage inference-making by making key structures and processes transparent, and can
eliminate extraneous information so that only information crucial to understanding is included (e.g. Larkin & Simon, 1987; Mayer, 1989; Dwyer, 1978).

Some of the advantages of learning from external visualizations should also be gained from producing them. However, students primarily use language (both oral and written) in classrooms and on exams. When drawing and diagrams are used in classrooms, students are generally instructed to interpret and learn from others’ visualizations. It is much less likely for students to create their own visual explanations as a way of developing and displaying their understanding. However, producing diagrams is a form of active learning and many studies have shown that learning is enhanced when students are actively engaged in creative, generative activities (e.g. Chi, 2000; Hall, Bailey & Tillman, 1997).

In the present experiments, students are given pencil and paper and are asked to produce either visual (drawn) or verbal (written) explanations of STEM (science, technology, engineering and mathematics) concepts for systems that are only partially observable. Both the information included in the visual and verbal explanations and the consequences for learning will be examined. Although visualizations can readily depict the parts of a system, the shapes of parts, and the configuration of the parts, it is more difficult to depict the operation of a system, its functionality, and the causal mechanisms. Of course, the configuration provides clues for the system’s operation and causality, and visual information can be supplemented with non-depictive diagrammatic devices, notably arrows (Heiser & Tversky, 2006, Tverksy et al., 2000; Tversky, 2002, 2011). Language has words for some parts, configurations, actions, and causes, but complex and complete descriptions of spatial and dynamic systems can be difficult to produce. Even for simple routes in familiar environments, crucial information is omitted in purely verbal explanations (e.g. Heiser, Tversky, & Silverman, 2004). In addition, visual explanations are
usually augmented by words, but, as shall be seen, verbal explanations are not usually augmented by diagrams. A combination of visual and verbal material usually helps learning (i.e. Paivio, 1990; Mayer, 2001, 2005). In particular, a substantial body of research suggests that supplementing visualizations with text helps learners to construct internal representations (mental models) of a system (e.g. Mayer, 1989; Hegarty, Carpenter & Just, 1990; Hegarty & Just, 1993).

Importantly, visual explanations demand completeness. Just like other types of models, i.e. physical or mathematical, all of the essential parts of a system need to be represented in the proper configuration in order for it to work. In this way, drawings provide a visual check for completeness that verbal descriptions do not require. Inferences can then be made from diagrams that preserve and map the parts and configuration of the represented system or process.

Finally, when asked to take notes while reading a text that they could later use to answer questions about the text, many students use only language, but those who make diagrams perform better (Schneider et al., 2010). Furthermore, requiring diagrams benefited all students. For all these reasons, it was expected that more information would be included in visual rather than verbal explanations. Even though no further instruction was provided after participants generated explanations, students who produce visual explanations may perform better on a post-test than those who do not because producing a visual explanation helps consolidate the information into a coherent mental model of a system.
CHAPTER 2
LITERATURE REVIEW

2.1 Difficulties in Learning Invisible Processes in Science

Student difficulty with learning complex processes in science has been well documented (e.g. Posner et al., 1982; Perkins & Grotzer, 2005). Student understanding is often inaccurate or incomplete, and processes with invisible components pose particular challenges. Some scientific processes or devices are invisible due to their size, or because they contain structural components that are hidden from view or are contained within other components. Other concepts in science are inherently invisible, i.e. gravity, wind, and other forces. Still other aspects, such as causality, must be inferred.

Understanding a scientific process involves learning the structure of the system, how the parts are arranged spatially and relatively in the system, and also how the parts interact in a causal way for the system to function. Scientific processes usually follow a particular sequence of changes in the structure and spatial arrangement of the components. Understanding these processes, then, involves the development of a mental model: "a cognitive representation of the essential parts of a system as well as the cause-and-effect relations between a change in the state of one part and a change in the state of another part" (Mayer, 1998).

Research in several domains in science has found that students tend to focus on perceptually available structural features instead of functional characteristics. Chi, DeLeeuw, Chiu, & Lavancher (1999) found that students explaining the circulatory system experienced difficulty with implicit functional features. In a study comparing novices with experts, Hmelo-Silver & Pfeffer (2004) found that participants represented salient structural features of an
aquatic ecosystem much more than behavioral or functional features, and behavioral features with dynamic, invisible processes were the most difficult for participants to represent.

Some topics involve a plethora of hidden structure and function and may be particularly difficult to understand. For example, plate tectonics involves processes taking place inside the Earth, which is obviously outside of our direct experience, operating on a grand size scale, and occurring on a time scale that greatly surpasses our reference point of a human lifetime (Gobert, 2005). In order to build a rich mental model of this system, learners must first gain structural understanding of the various layers of the earth as well as functional understanding of the causal movements within the layers.

This literature review reflects a great deal of scholarship on the learning of invisible processes in chemistry. The teaching of chemistry is essentially universal in science education, giving rise to many efforts to improve said teaching. Many of the principles of teaching the invisible or complex processes in chemistry may be applicable to other content areas.

Chemistry includes a number of complex, invisible concepts that are difficult to understand. Bonding, solutions, and chemical changes are some of the most studied concepts due to their abstract nature. Much of what is chemistry exists at a molecular level and is not available for direct perception. Students’ understanding of chemical change may be limited to their observations of unusual and noticeable events, such as the production of a gas or a color change. Whereas the experiments used in classroom demonstrations are carefully selected to denote chemical processes by changing color, precipitating a solid, or giving off heat, most chemical reactions in the real world occur at rates that are so fast or slow, or their products are so dispersed, colorless, or odorless, as to make them difficult to detect.
In addition, students may make inappropriate or unfounded generalizations based on what they can observe. They may use the macroscopic properties of a substance to infer its particle properties, that is they reason from big to small. Student use the visible attributes of matter to make inferences about the invisible. For example, students may believe that copper atoms are red-brown because that is the color of copper (Ingham & Gilbert, 1991), or believe that if a substance is malleable, then the atoms themselves are malleable as well (Ben-Zvi, Eylon, & Silberstein, 1986).

Students are challenged by processes that require them to move between different levels of representation (Wilensky & Resnick, 1999). For example, understanding chemical processes involves taking into account the macroscopic (observable), submicroscopic (particles of matter/atoms) and the symbolic conventions used to represent the submicroscopic (chemical formulas and equations). Students need to be able to move between these three levels to fully understand function, but instruction in basic chemistry rarely acknowledges these challenges. Students have difficulty moving between these levels particularly because the macroscopic, “hands-on” part of chemistry is generally more interesting to students and doesn’t always reflect sub-microscopic behavior (e.g. Johnstone, 1991, Wang, 2008).

2.2 Learning from Representations in Science

Given the inherent challenges in teaching and learning complex or invisible processes in science, educators have developed ways of representing these processes to enable and enhance student understanding. Teaching complex systems in science usually involves presenting explanations via text and/or external visual representations. External visual representations, including diagrams, photographs, illustrations, flow charts, and graphs, are often used in science
to both illustrate and explain concepts (Hegarty, Carpenter, & Just, 1990; Mayer, 1989). While visual representations are often used in textbooks as a purely illustrative adjunct to explanations in text, they have the potential to significantly aid learning for a number of reasons, including limiting the number of possible interpretations (Scaife & Rogers, 1996). Diagrams are able to explicitly indicate structural relationships because they encourage inference making based on perceptual cues such as spatial adjacency (Larkin & Simon, 1987). Iconic, as in more pictorial, diagrams in particular are able to make structural information explicit (Seel & Strittmatter, 1989), but while understanding structure is key, understanding the process, function, and behavior is generally the goal. Students may not always know how to learn from diagrams effectively, however, and novices may experience particular difficulty in being able to break down the structural elements in a diagram according to their relevant properties (Lowe, 1989; Wilkin, 1997). Novices lacking prior knowledge may also be at a particular disadvantage when interpreting schematic diagrams, such as those of electric circuits, which are abstractions of a physical system (Petre & Green, 1993).

Schwartz & Heiser (2006) discuss four perceptual processes that are particularly relevant: effortless structure, determinism, action coupling, and pre-interpretation. Because perceptual processes are automatic, many aspects of visual information become available with little cognitive effort. Determinism refers to the fact that perceptual structure is more unambiguous, because spatial relations are determined. Properties such as size, shape, and proximity are forced to be specific in the construction of a visual representation. Schwartz and Heiser (2006) argue that determinism in visual representations may be useful because it forces the creator of the representations to make specific choices about the placement of objects, while in language there is more opportunity for ambiguity.
Learning from representations may depend on individual differences in the learners. Davenport et al. (2007) argue that because diagrams make relevant information salient, they may be particularly helpful for low knowledge learners. In their study on chemical equilibrium, they compared two lectures; one was traditional, one with designed diagrams. Low performing students in the diagram group outperformed the traditional group, almost reaching the level of the highest performing students.

Learning from representations in science also involves integrating different external representations to form internal representations. Mayer and colleagues (2005) have developed a Cognitive Theory of Multimedia Learning (CTML). In order for learners to achieve the greatest potential learning outcomes while learning with multimedia, they must be able to translate between various sources of information, including diagrams, text, and videos with narration.

Ainsworth (2006) argues that multiple representations play several major roles in learning. First, different representations each provide separate types of information to the learner that complement each other. Second, they constrain possible interpretations by familiarity or by inherent properties. Last, they likely aid learners by supporting abstraction, promoting generalization to novel situations, and by demonstrating relations among representations. Written and visual representations may work together to provide a complete “picture” of the process.

Mayer (1993) showed that the type of information best suited to summarizing a scientific explanation is an explanative illustration: a sequence of frames depicting the major steps in the process. In addition, they are most effective when they include concise captions describing each frame in words (Mayer, 1989; Mayer & Gallini; Mayer et al., 1995). In a provided diagram,
learners must integrate the information in a meaningful way, examining relationships, spatial contiguity, redundancy etc.

2.3 Learner-generated Explanations

Learners may have difficulty learning from diagrams created by others, thus an important learning strategy to consider is learner-generated explanations of scientific phenomena. Explanations convey information about concepts or processes with the goal of making clear and comprehensible an idea or set of ideas. Explanations may involve a variety of elements, such as the use of examples and analogies (Roscoe & Chi, 2007). When explaining something new, learners may have to think carefully about the relationships between elements in the process and prioritize the multitude of information available to them. Generating explanations may require learners to reorganize their mental models by allowing them to make and refine connections between and among elements and concepts. Explaining may also help learners metacognitively address their own knowledge gaps and misconceptions.

Wittrock’s (1990) generative theory stresses the importance of learners actively constructing and developing relationships. When learners make connections between information, knowledge, and experience, by generating headings, summaries, pictures, and analogies, deeper understanding develops. Other researchers clarify the significance of the learner’s activities. Chi (2009) differentiates between active, constructive, and interactive learning activities and hypothesizes that interactive activities (e.g. working with a tutor to solve problems) may be better than constructive activities (e.g. note-taking), which in turn are better than active activities (e.g. underlining a text while reading). Additional studies support these ideas. For example, Stern et al. (2003) showed that actively creating graphs was a better learning
strategy than merely viewing presented graphs. Chi et al. (1989, 1994) found that high-performing students produced more self-explanations than low-performing students in physics and biology, suggesting that more engagement with material lends itself to greater understanding. From a learner’s perspective, active, constructive, and interactive activities engage different cognitive processes: eliciting attention, creating and restructuring new knowledge, and jointly creating processes, all of which are better than passive activities. Active construction requires learners to become aware of specific elements and to learn to organize their knowledge in new ways and link to other content. Generating explanations is a constructive activity since it requires students to select information and choose how to integrate and represent the information in a unified way.

Hausmann & Vanlehn (2007) addressed the possibility that generating explanations is beneficial because learners merely spend more time with the content material than learners who are not required to generate an explanation. In their study, they compared the effects of using instructions to self-explain with instructions to merely paraphrase physics (electrodynamics) material. Attending to provided explanations by paraphrasing was not as effective as generating explanations as evidenced by retention scores on an exam twenty-nine days after the experiment and transfer scores within and across domains. Their study concludes “the important variable for learning was the process of producing an explanation” (p. 423).

Mayer and colleagues have conducted several experiments that have shown a learning benefit to generative activities in several different domains involving invisible components, including electric circuits (Johnson & Mayer, 2010), lightning formation (Johnson & Mayer, 2009), and the chemistry of detergents (Schwamborn et al., 2010). These studies represent significant findings in the area of learner-generated visual explanations.
There are other factors, of course, that likely influence the utility of generating explanations as a learning strategy. For example, Witherspoon et al. (2007) showed that learners who spent more time constructing external representations performed better on post-tests examining both factual and conceptual knowledge of the human circulatory system. Methodological differences abound in the studies mentioned on generating explanations. Some studies prompt participants at regular intervals to explain; other studies provide participants with pre-drawn elements to include in their explanations. In addition, few studies have investigated the role of individual differences in the construction of visual representations.

2.4 Learner-generated Explanations in Visual and Verbal Formats

In addition to the scholarship on learner-generated visual explanations, there exists a great deal of work on the utility of written explanations. Traditionally, students are engaged in explanation activities as an assessment tool, on tests, lab reports etc. and are usually asked to explain their understanding of concepts in words. A number of researchers have argued for students to construct written explanations as a way of developing understanding in science and also as a way of developing writing skills (e.g. Bass, Baxter, & Glaser, 2001). Written explanations, particularly in student lab notebooks, have been presented as a way to monitor teacher instruction and student learning. The claim is that the development of mental representations and construction of language can lead to improved learning (e.g. Brown & Campione, 1990). Brown & Campione (1990) argue that asking students to write explanations pushes them to evaluate, integrate, and elaborate on their knowledge in new ways. The ability to reflect on knowledge and understanding in a metacognitive way is increased with the generation
of written explanations compared to oral exchanges because of the greater cognitive demands placed on the writers.

However, many researchers and educators have voiced support for encouraging students to actively create their own visual representations. The importance of visual explanations is well supported, and some researchers have demonstrated their superiority over written explanations. For example, Alesandrini (1981) compared college students constructing drawings with a group that paraphrased sections of text, and the drawing participants outperformed the paraphrase group. Gobert & Clement (1999) investigated the effectiveness of student-generated diagrams versus student-generated summaries on understanding plate tectonics after reading an expository text. Students who generated diagrams scored significantly higher on a post-test measuring spatial and causal/dynamic content, even though the diagrams contained less domain-related information. Hall, Bailey, & Tillman (1997) showed that learners who generated their own illustrations from text performed equally as well as learners provided with text and illustrations. Both groups outperformed learners only provided with text. In a study concerning the law of conservation of energy, participants who generated drawings scored higher on a post-test than participants who wrote their own narrative of the process (Edens & Potter, 2003). In addition, the quality and number of concept units present in the drawing/science log correlated with performance on the post-test. Van Meter (2001) found that drawing while reading a text about Newton's Laws was more effective than answering prompts in writing. Finally, Witherspoon et al. (2007) showed that generating external representations while studying the circulatory system increased scores compared to re-reading the provided text.

Van Meter & Garner's (2005) "Generative Theory of Drawing Construction" posits that generating visual representations encourages learners to actively engage in cognitive and
metacognitive processing, thus fostering a deep understanding of the material. Learners must select and organize the relevant information, create a mental model of the information, and then draw a representation based on their mental images. Visual explanations may act like sketches, such as those that are produced to provide directions; they omit relevant information and highlight and prioritize essential information. The authors argue that deep understanding occurs when and because students are actively engaged in the process. However, students who are overly concerned with the quality and accuracy of their drawing may not experience this benefit to the fullest extent, and students who lack sufficient prior knowledge may have difficulty with selecting and organizing appropriate information.

The cognitive processes underlying the development of understanding may differ for visual and verbal explanations. What do we already know about these differences? If visual representations are preferable, why? One aspect to explore is that there are different types of information in visual and verbal explanations, and learning advantages for the generation of visual explanations could be attributed to learners’ translating across modalities, from a verbal format into a visual format. Translating verbal information from the text into a visual explanation may promote deeper processing of the material and more complete and comprehensive mental models (Craik & Lockhart, 1972). Ainsworth & Iacovides (2005) addressed this issue by asking two groups of learners to self-explain while learning about the circulatory system of the human body. Learners given diagrams were asked to self-explain in writing, and learners given text were asked to explain using a diagram. The results showed no overall differences in learning outcomes, however the learners provided text included significantly more information in their diagrams than the other group. Aleven & Koedinger (2002) argue that explanations are most helpful if they can integrate visual and verbal information. Translating across modalities may
serve this purpose, although translating is not necessarily an easy task (Ainsworth, Bibby, & Wood, 2002). Importantly, in the studies described previously, the explanations were requested of the students; less is known about how students may choose to represent information when they are not given specific prompts to do so.

Studies vary in the level of external support that they provide learners, and Van Meter (2001) argues that these differences account for the inconsistent findings in the usefulness of drawing as a learning strategy. In its purest form, participants create drawings without any support. Participants provided with extensive support may receive components of the drawing or a background, or prompts to draw at particular point in the accompanying text. Several studies have found that when supports help participants generate the most accurate pictorial representations, they also generate the highest scores on post-test learning outcome measures.

Paivio’s dual-coding theory (1990) and Wittrock’s (1989) generative theory provide a theoretical basis for learner-generated visual representations as a strategy for learning in science. Paivio (1990) argued that information is coded and represented both visually and verbally in memory. When information is coded in both systems and connections are made between them, a generative process has occurred. Generating explanations likely requires the integration of information in these systems, and is therefore likely to increase conceptual understanding. Learner-generated explanations may also help the learner by enabling them to elaborate and express information in a unique, personally meaningful way.

As mentioned earlier, Van Meter & Garner (2005) present a theoretical framework for learning from drawing: the Generative Theory of Drawing Construction. This theory builds on Mayer’s Generative Theory of Textbook Design (e.g. Mayer et al., 1995; Mayer & Gallini, 1990). In Mayer’s theory, readers construct internal verbal representations of words as they read,
and also internal nonverbal representations of illustrations when reading illustrated text. He argues that these representations, while separate, are connected by referential connections, and this integrated representation develops into the learner’s mental model of the content (e.g. Mayer, 1993). In Van Meter & Garner’s theory, learners must select, organize, and integrate information, in a process that is unlikely to be linear. Internal verbal and nonverbal representations are linked and inform the drawing process. This integration of verbal and non-verbal formats is a required component of learner-generated drawing, and important to distinguish between integration that may occur when verbal and non-verbal material are presented to the learners, such as illustrations to accompany text.

It is important to review that not all studies have found advantages to generating explanations. Wilkin (1997) found that directions to self-explain using a diagram hindered understanding in examples in physical motion when students were presented with text and instructed to draw a diagram. She argues that the diagrams encouraged learners to connect familiar but unrelated knowledge. In particular, “low benefit learners” in her study inappropriately used spatial adjacency and location to connect parts of diagrams, instead of the particular properties of those parts. Wilkin argues that these learners are novices and that experts may not make the same mistake since they have the skills to analyze features of a diagram according to their relevant properties. She also argues that the benefits of self-explaining are highest when the learning activity is constrained so that learners are limited in their possible interpretations. Other studies that have not found a learning advantage with generating drawings have in common an absence of support for the learner (Alesandrini, 1981; Leutner, Leopold, & Sumfleth, 2009).
2.5 The Role of Spatial Ability in Learner-generated Explanations

Spatial thinking involves objects, their size, location, shape, their relation to one another, and how and where they move through space. Developing an understanding of scientific phenomena seems to require the use of spatial ability. How then, might learners with different levels of spatial ability gain structural and functional understanding in science, and how might this ability affect the utility of learner-generated visual explanations?

Developing an ability to visually manipulate a model of scientific processes is complicated. In constructing a visual representation of a scientific process, people may need to first imagine actions. Several lines of research have sought to explore the role of spatial ability in learning science. Kozhevnikov, Hegarty, & Mayer (2002) found that low spatial ability participants interpreted graphs as pictures, whereas high spatial ability participants were able to construct more schematic images and manipulate them spatially.

Hegarty & Just (1993) found that the ability to mentally animate mechanical systems correlated with spatial ability, but not verbal ability. In their study, low spatial ability participants made more errors in movement verification tasks. In addition, Hegarty & Steinhoff (1997) found that low spatial ability learners who were encouraged to make notes on diagrams performed better on motion verification tasks than low ability learners who did not take notes. (Making notes did not increase learning for high spatial ability participants). Leutner, Leopold & Sumfleth (2009) found no effect of spatial ability on the effectiveness of drawing compared to mentally imagining text content.

Heiser & Tversky (2002) found that low spatial and high spatial participants differed in the instructions they constructed to give to others to assemble a TV cart. Low spatial ability participants were more likely to construct 2-D menus of parts, and neglected the use of
perspective. High spatial participants were more likely to produce step-by-step action diagrams in 3-D, they enlarged the small parts, and they used extra-pictorial features such as arrows.

Mayer & Sims (1994) found that spatial ability played a role in participants’ ability to integrate visual and verbal information presented in an animation. The authors argue that their results can be interpreted within the context of dual-coding theory. They suggest that low spatial ability participants must devote large amounts of cognitive effort into building a visual representation of the system, and high spatial ability participants are more able to allocate sufficient cognitive resources to building referential connections between visual and verbal information. In order to benefit from generating explanations, students need to engage in active cognitive processing, selecting and organizing relevant information, and translating prior knowledge across modalities. Students must also possess sufficient prior knowledge to be able to complete the task, and the task must not overwhelm resources in working memory.

Another important characteristic of spatial ability is that it can change over time. In some studies, low spatial ability students show little or no initial improvement, but it rapidly improves over time (Terlecki et al., 2008). High ability learners also show improvement, and even quicker than low ability learners. Although individual differences may play a role in the cognitive conditions required for meaningful learning from words and pictures, the importance of this way of learning for all students should be further explored.

2.6 Summary

The purpose of the present research is to develop an understanding of how learner-generated explanations may increase learning and understanding of invisible processes. The process of generating an explanation may provide advantages over provided explanations by
requiring learners to make connections between both verbal and non-verbal pieces of information. Developing these connections helps learners form a deep mental model of the process. Visual explanations drawn by learners may be particularly useful for many reasons. Developing understanding requires active information processing; thus it is likely influenced by the abilities of the learner. Based on the review of the literature, the role of the information contained in generated explanations and of spatial ability has yet to be clarified.
CHAPTER 3
EXPLAINING THE FUNCTION OF A MECHANICAL SYSTEM: THE BICYCLE TIRE PUMP

3.1 Experiment 1 Introduction

Experiment 1 examined visual and verbal explanations of the function of a bicycle tire pump generated by participants with low and high spatial ability. Although the pump itself is not invisible, components of its function are hidden from the user. These components, notably the inlet and the outlet valve, are hidden because of their location inside of the pump and because their function depends on the movement of air. It was predicted that visual explanations would include more information than verbal explanations, particularly structural information, since their construction encourages completeness and the production of a whole mechanical system. It was also predicted that functional information would be biased towards a verbal format, since much of the function of the pump is hidden and difficult to express in pictures. Because understanding how elements of the pump interact is crucial to understanding its function, including more functional information should lead to better performance on the post-test. Finally, it was predicted that high spatial ability participants would be able to produce more complete explanations, and would thus also demonstrate better performance on the post-test.
3.2 Method

3.2.1 Participants

Participants were 127 7th and 8th grade students, ages 12-14, enrolled in an independent school in New York City. Of the 127 students, 59 were females, and 68 were males. Written parental consent was obtained by means of signed informed consent forms.

3.2.2 Design

Each participant was randomly assigned to one of two conditions. Sixty-four participants in the visual condition studied the pump and explained its function by drawing, and sixty-three participants in the verbal condition explained the pump’s function by writing. Participants in both conditions were administered the same 16 question post-test following the completion of their explanations. All participants were administered the Vandenberg-Kuse Mental Rotation Test (MRT) as a measure of spatial ability.

3.2.3 Materials

The materials consisted of a bicycle tire pump, the Vandenberg-Kuse Mental Rotation Test (MRT), two versions of the instructions, and the post-test. All of the paper materials were typed on 8.5 x 11 sheets of paper. A blank 8.5 x 11 sheet of paper was also provided for the explanations. The bicycle tire pump was a 12-inch Spalding pump. The pump’s chamber and hose were made of clear plastic; the handle and piston were black plastic. The Vandenberg-Kuse MRT (Vandenberg & Kuse, 1978), is a twenty item test in which two-dimensional drawings of three-dimensional objects are compared (Appendix B). Each item consists of one “target” drawing and four drawings that are to be compared to the target. Two of the four drawings are
rotated versions of the target drawing, and the other two are not. The task is to identify the two
rotated versions of the target. A score was determined by scoring items as correct and given one
point if both of the correct rotated versions were chosen. The maximum score was twenty points.

The post-test (see below) consisted of sixteen true/false questions printed on a single
sheet of 8.5 x 11 paper. Half of the questions related to the structure of the pump, and the other
half related to its function. The questions were adapted from Heiser & Tversky (2002b).

_______ 1. The piston never touches the wall of the cylinder.
_______ 2. Pressure build-up in the cylinder chamber opens the outlet valve.
_______ 3. The piston is attached to the handle.
_______ 4. When the handle is pulled up, the inlet valve opens.
_______ 5. The outlet valve is at the top of the piston.
_______ 6. Air enters the chamber when the handle is pulled up.
_______ 7. The inlet valve closes when the handle is pushed down.
_______ 8. The inlet valve is open when the outlet valve is closed.
_______ 9. The downward movement of the piston causes the inlet valve to close.
_______ 10. The outlet valve is open when the piston is raised.
_______ 11. The outlet valve allows air to enter the chamber.
_______ 12. The pump will not work if the outlet valve stays open.
_______ 13. Next to the handle is the inlet valve.
_______ 14. Next to the hose is the outlet valve.
_______ 15. The outlet valve is in the middle of the chamber.
_______ 16. The inlet valve is inside the piston.
3.2.4 Procedure

The experiment was conducted over the course of two non-consecutive days during the normal school day and during regularly scheduled class time. On the first day, participants completed the Vandenberg-Kuse Mental Rotation Test as a whole-class activity. Participants without parental consent worked quietly at their desks. First, participants were given the packet containing the MRT and instructions. Participants were read aloud the instructions and were also instructed to read silently as the directions were being read. Next, they were given untimed practice on several items to be sure they understood the task. Participants were given three minutes to complete items 1-10, and an additional three minutes to complete items 11-20.

On the second day, participants were individually asked to study the bike pump and were then asked to generate explanations of its function. The 127 participants were randomly assigned to either the visual or the verbal condition, yielding 64 participants in the visual condition and 63 participants in the verbal condition.

Participants were tested individually in a quiet room away from the rest of the class. Each participant was given a packet containing one page of instructions and a blank page for their explanations. They were also provided with an actual bicycle tire pump. A third page with the 16 question post-test on the structure and function of the pump was given upon completion of the explanation. The instruction sheet was read aloud to participants and they were instructed to read along as the instructions were read. The first set of instructions was as follows: “A bicycle pump is a mechanical device that pumps air into bicycle tires. First, take this bicycle pump and try to understand how it works. Spend as much time as you need to understand the pump.”
The next set of instructions differed for participants in each condition:

Visual Condition: “Then, we would like you to **draw** your own diagram or set of diagrams that explain how the bike pump works. Draw your explanation so that someone else who has not seen the pump could understand the bike pump from your explanation. Don't worry about the artistic quality of the diagrams; in fact, if something is hard for you to draw, you can explain what you would draw. What's important is that the explanation should be primarily visual, in a diagram or diagrams.”

Verbal Condition: “Then, we would like you to **write** an explanation of how the bike pump works. Write your explanation so that someone else who has not seen the diagram could understand the bike pump from your explanation.”

The final set of instructions for all participants were as follows:

“You may not use the pump while you create your explanations. Please return it to me when you are ready to begin your explanation. When you are finished with the explanation, you will hand in your explanation to me and I will then give you 16 true/false questions about the bike pump. You will not be able to look at your explanation while you complete the questions.”

Participants’ study time was self-terminating. Participants were given the 16 question post-test after finishing their explanations. All students finished within the 45 minute class period.
3.3 Coding

3.3.1 Coding for Structure and Function

A subset of the explanations (20%) was coded by both the author and another researcher in educational psychology. Both scorers used the same coding system as a guide. The percentage of agreement between scores was calculated and was found to be above 90% for all measures. Disagreements were resolved through discussion. The author then scored the remainder of the explanations.

Each explanation included a maximum score of twelve points for structure: two points for each of the following six components: chamber, piston, inlet valve, outlet valve, handle, and hose. Table 3-1 shows the coding guide for structure. In visual explanations, one point was given for a component drawn correctly, and one additional point if the component was labeled correctly. For verbal explanations, sentences were divided into propositions, the smallest unit of meaning in a sentence. Descriptions of the systems’ structural location i.e. at the end of the piston is the inlet valve, or of features of the components (i.e. the shape of a part) counted as structural components. In the example on the left in Figure 3-1, the chamber and the piston were each given a score of 2 points since they were both labeled and depicted correctly. The inlet valve and the outlet valve were each given a score of only one point since their location was correctly identified, but their structure was not clearly depicted.
Table 3-1.

**Coding guide for structure.**

<table>
<thead>
<tr>
<th>Type of Explanation</th>
<th>Visual</th>
<th>Verbal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part drawn correctly (1 pt.)</td>
<td>Description of a part (i.e. the chamber is a long hollow cylinder) (1 pt.)</td>
<td></td>
</tr>
<tr>
<td>Part with location/label (1 pt.)</td>
<td>Part named with location (i.e. the outlet valve is located at the closed end of the cylinder) (1 pt.)</td>
<td></td>
</tr>
</tbody>
</table>

Information was coded as functional if it depicted or described the function/movement of an individual part, or the way multiple parts interact. Each component was given one point (Table 3-2). There was no limit to the number of functional units coded in each explanation; no explanation contained more than ten functional units.

Table 3-2.

**Coding guide for function.**

<table>
<thead>
<tr>
<th>Type of Explanation</th>
<th>Visual</th>
<th>Verbal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function/movement of an individual part with arrow</td>
<td>Function/movement of an individual part</td>
<td></td>
</tr>
<tr>
<td>Function/movement of multiple parts with arrows</td>
<td>Function/interaction of multiple parts</td>
<td></td>
</tr>
</tbody>
</table>


In the example on the right in Figure 3-1, one point was given for air entering the chamber, one point was given for air being sealed into the pump by the piston, one point was given for air being pushed out of the pump, and one point was given for air exiting the chamber for a total of four functional points. Each component of structural and functional information was tallied to give a total structural and functional score for each explanation.

### 3.3.2 Coding of Essential Features

To further establish a relationship between the explanations generated and outcomes on the post-test, explanations were also coded for the inclusion of information essential to its function according to a four-point scale (adapted from Hall, Bailey, & Tillman, 1997). One point was given if both the inlet and the outlet valve were clearly present in the drawing or described in writing, one point was given if the piston inserted into the chamber was shown or described to be airtight, and one point was given for each valve if they were shown or described to be opening/closing in the correct direction. The maximum score for essential features was four
points. In the visual explanation shown in Figure 3-2, the score given for essential features was one point, for the depiction of an airtight seal between the piston and the chamber. In the verbal explanation shown in Figure 3-3, the score given was the maximum of four points, since it includes all of the essential features.

Figure 3-2. Example of visual explanation showing a tight seal between the piston and the chamber.
When you pull on the handle the piston is pulled out of the barrel. The friction against the sides of the chamber pushes the black ring on the inlet valve against the lower edge (assuming the outlet valve faces down) of the inlet valve. This allows air to be taken in through gaps opened in the inlet valve. Because the outlet valve only allows air to leave the chamber through it, air can't enter through it. Air comes in through the inlet valve to fill the vacuum in the chamber when the piston was removed. When you push the handle back into the chamber, the piston is pushed pressed against the top of the inlet valve. This forms an air-tight seal. Because air cannot escape through the inlet valve, it is forced through the outlet valve.

Figure 3-3. Example of verbal explanation coded for the maximum of four points for essential features.
3.3.3 Coding of Invisible Features

The bicycle tire pump, like many mechanical devices, contains several structural features that are hidden or invisible and must be inferred from the function of the pump. The presence of three invisible features (the inlet valve, the outlet valve, and the movement of air) were coded separately. One point was given for the presence of each valve, and the correct movement of air was coded for a maximum of three points: air entering the pump, moving through the pump, and exiting the pump. The maximum score for invisible features was thus five points. In the verbal example shown in Figure 3-4, one point was given for each valve, one point was given for air moving through the cylinder, and one point was given for air exiting the pump, for a total of four points.

Figure 3-4. Example of verbal explanation describing invisible features.
3.3.4 Coding Visual Elements: Arrows and Multiple Steps

Additional information contained in visual explanations was coded separately: the use of arrows and the use of multiple steps/frames. Arrows were commonly used in visual explanations for three main purposes: to label a part or an action, to show motion, or to indicate sequence. Each use of arrows was coded for one of these purposes and a score tallied for each use. The use of multiple steps/frames was used to show starting and ending positions, and change in location of parts of the pump and air (see Figure 3-5). The number of steps/frames was tallied for each explanation. Some visual explanations also included a change in perspective, or a “zoom” feature of particular parts, however these were too few to be included in statistical analyses (see Figure 3-6).

![Figure 3-5. Example of visual explanation depicting multiple steps.](image-url)
3.4 Results

3.4.1 Spatial Ability

Participants’ scores on the MRT were used to divide students into low and high spatial participants based on a median split in the data. Scores on the MRT range from 0-20; the mean score for participants was 10.56, and the median was 11. Scores were significantly higher for males (M = 13.5, SD = 4.4) than for females (M = 8.8, SD = 4.5), F(1, 126) = 19.07, p < .01. Gender differences are typical; this result replicates that of other studies (e.g. Heiser & Tversky, 2002). Low and high spatial ability participants were equally distributed in the visual and verbal groups.
3.4.2 Structure and Function

The total points for structural and functional information were tallied for visual and verbal explanations (Table 3-3 and Figure 3-7). Both visual and verbal explanations contained from two to ten structural components and zero to ten functional components. Visual explanations contained a significantly greater number of structural components (M = 6.05, SD = 2.76) than verbal explanations (M = 4.27, SD = 1.54), F(1, 126)=20.53, p<.05, while there was no difference in the number of expressed functional components between visual and verbal explanations.

Table 3-3.

Number of structural and functional units in visual and verbal explanations of the bicycle pump.

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>Visual</th>
<th>Verbal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Structure</td>
<td>6.05</td>
<td>2.76</td>
</tr>
<tr>
<td>Function</td>
<td>3.98</td>
<td>2.80</td>
</tr>
</tbody>
</table>
Many visual explanations (67%) contained verbal components, thus the explanations were coded for the number of structural and functional units contained in pictures and words. Structural and functional information were equally likely to be expressed in words or pictures in visual explanations (Figure 3-8). There were no significant differences between low spatial (M = 5.15, SD = 2.21) and high spatial (M = 4.62, SD = 2.16) participants in the number of structural units. There were also no significant differences between low spatial (M = 3.83, SD = 2.51) and high spatial (M = 4.10, SD = 2.13) participants in the number of functional units.
3.4.3 Essential Features

Visual and verbal explanations were coded for the inclusion of essential information on a four-point scale. These scores were significantly higher for visual explanations (M = 1.78, SD = 1.0) than for verbal explanations (M = 1.20, SD = 1.21), F(1, 126) = 7.63, p<.05 (see Figure 3-9). No significant differences in these scores were found between low (M = 1.34, SD =1.04) and high spatial participants (M = 1.45 , SD =1.2). Essential features were also found to positively correlate with delayed post-test scores, r= .197, p<.05.

Figure 3-8. Number of structural and functional units contained in words and pictures.
3.4.3 Invisible Features

The presence of three invisible parts were coded separately: the inlet valve, the outlet valve, and the movement of air. Scores for the inlet valve were higher for visual explanations ($M = .67, SD = .45$) than verbal explanations ($M = .51, SD = .5$), however the effect was only marginally significant $F(1, 126) = 3.13, p=.07$. Scores for air movement also showed a marginally significant difference, $F (1,126) = 2.93, p=.09$, with visual explanations ($M =2.35, SD = 1.28$) containing a greater number than verbal explanations ($M = 1.88, SD = 1.45$). No significant differences between visual ($M = .92, SD = .43$) and verbal explanations ($M = .79, SD = .65$) were found for the outlet valve. Analysis of the invisible parts between low and high spatial participants also failed to show any significant differences in the inclusion of the inlet valve, the outlet valve, or air movement. Finally, a total score for the inclusion of invisible parts was calculated for each participant by totaling the scores for the inlet valve, the outlet valve, and
for air movement. The mean score was 3.26, SD=1.25. The data was analyzed using linear regression, and revealed that the total score for invisible parts significantly predicted scores on the post-test, $F(1, 118) = 3.80, p=.05$.

![Figure 3-10. Scores for the inlet valve in visual and verbal explanations.](image)

### 3.4.4 Arrows

Analysis of visual explanations revealed that 87% contained arrows. Arrows were most commonly used as labels ($M = 3.85$, $SD = 1.2$), see Figure 3-11. No significant differences were found between low and high spatial participants on arrows used to label, movement of parts or air, or to indicate sequence. No significant correlations were found between the use of arrows and learning outcomes measured on the post-test.
3.4.5 Multiple Steps

The use of multiple steps/frames to show sequence and change over time was found in 39% of visual explanations. There were no significant differences between low spatial (M = 1.40, SD = 1.26) and high spatial (M = 1.43, SD = .87) participants. The number of steps used by participants ranged from one to six. Participants whose explanations contained more than a single step scored significantly higher (M = .76, SD = .18) on the post-test than participants whose explanations consisted of a single step (M = .67, SD = .19), F(1, 126) = 5.02, p<.05, see Figure 3-12.
Figure 3-12. Scores on post-test for explanations containing a single step and multiple steps.

3.4.6 Learning Outcomes

Scores, defined by proportion correct, on the post-test by group and spatial ability are shown in Figure 3-13. A test of the overall interaction between group and spatial ability was significant, $F(1, 124)=4.094$, $p<.01$. In particular, low spatial participants who generated verbal explanations had significantly lower scores ($M=.609$, $SD=.145$) than low spatial participants who drew explanations ($M=.716$, $SD=.121$) or high spatial participants who created either visual ($M=.701$, $SD=.092$) or verbal ($M=.726$, $SD=.112$) explanations. Analyzing structure and function questions separately on the post-test found no differences in performance between low and high spatial participants on structural questions. Finally, analyzing performance on functional questions found a significant effect: low spatial participants who generated verbal explanations ($M=.502$, $SD=.194$) scored significantly lower than low spatial participants who drew ($M=.678$, $SD=.122$) or high spatial participants who created either visual ($M=.678$, $SD=.141$) or verbal explanations ($M=.703$, $SD=.125$), $F(1, 126)=9.498$, $p<.05$, see Figure 3-14.
Figure 3-13. Scores on the post-test, by group and spatial ability.

Figure 3-14. Scores on functional questions on the post-test, by group and spatial ability.
3.5 Discussion

The results of Experiment 1 provide some support for the use of learner-generated visual explanations in developing understanding of a new scientific system. The results show that low spatial ability participants were able to learn as successfully as high spatial ability participants when they first generated an explanation in a visual format. Importantly, this result was particularly strong for functional understanding gained by low spatial participants who generated visual explanations.

Visual explanations may have led to greater understanding for a number of reasons. As discussed previously, visual explanations encourage completeness. They force learners to decide on the size, shape, and location of parts/objects. Understanding how the pump works (when air enters, when and how it can leave), gives clues as to where air openings are located and that they open and close in only one direction.

Visual explanations were more likely to contain certain features (function of the valves, airtight nature of the pump, and the movement of air) than verbal explanations. Including the inlet valve and attempting to explain its function is crucial because when the inlet valve is performing its function (opening/closing) it is inside the chamber, thus air entering or exiting cannot be felt by the user. (This is not the case for the outlet valve, the other hidden structural component, because the user can easily feel when the movement of the piston corresponds to air entering and exiting the pump). The inlet valve in particular was difficult for participants to understand. It was often labeled or described as the “part that pushes air.” Some participants make no mention of valves, and merely show or describe the airtight piston moving into the chamber to push air out of the hole at the bottom. Again, drawing encourages completeness. Participants creating accurate and complete visual representations realize that there needs to be a
way for air to enter the pump, remain in the pump (pump must be airtight) and leave the pump through a separate opening.

Importantly, the inclusion of invisible parts (both the inlet and outlet valves, as well as air movement) predicted performance on the post-test. This is not surprising, considering that if a student understands hidden/invisible parts enough to include them in an explanation, they likely have a global understanding of the system that includes more basic/easier to master components. Understanding the “hidden” function of the invisible parts is key to understanding the function of the entire system and requires an understanding of how both the visible and invisible parts interact. The visual format may have been able to elicit components and concepts that are invisible and difficult to integrate into the formation of a mental model. Understanding the bicycle pump requires understanding how all of these components are connected through movement, force, and function.

Visual explanations showed an advantage over verbal explanations in this study, particularly for low spatial ability participants. An analysis of the visual explanations revealed that 67% also added written components to accompany their explanation. Arguably, some types of information may be difficult to depict visually, and our verbal language has many possibilities that allow for specificity. The inclusion of text as a complement to visual explanations may be key to the success of learner-generated explanations and the development of understanding. Indeed, several studies by Mayer and colleagues have found that understanding a system is enhanced when text and pictures are presented simultaneously to learners (e.g. Mayer & Gallini, 1990).

A limitation of this study is that participants were not provided with detailed instructions for completing their explanations. Another limitation is that this experiment does not fully clarify
the role of spatial ability, since high spatial participants in the visual and verbal groups
demonstrated equivalent knowledge of the pump on the post-test. One possibility is that the
interaction with the bicycle pump prior to generating explanations was a sufficient learning
experience for the high spatial participants. This makes sense; hands-on interactive experiences
are effective learning situations (e.g. Flick, 1993) and high spatial ability participants may be
better able to imagine the movement and function of a system (e.g. Hegarty, 1992).

Experiment 1 examined learning a mechanical system with invisible (hidden) parts.
Participants were introduced to the system by being able to interact with an actual bicycle pump.
The utility of visual explanations may differ for scientific phenomena that are more abstract, or
contain elements that are invisible due to their scale. Experiment 2 addresses this possibility by
examining a sub-microscopic area of science: chemical bonding.
EXPLAINING A SUBMICROSCOPIC PROCESS: CHEMICAL BONDING

4.1 Experiment 2 Introduction

Experiment 2 examined visual and verbal explanations in an area of chemistry: ionic and covalent bonding. These processes are “invisible” for different reasons than the processes in the bicycle pump mechanical system studied in Experiment 1. In chemical bonding, invisible components engage in complex processes whose scale makes them impossible to observe. Chemistry is often regarded as a difficult subject; one of the essential or inherent features of chemistry which presents difficulty is the interplay between the macroscopic, sub-microscopic, and representational levels (e.g. Bradley & Brand, 1985; Johnstone, 1991; Taber, 1997). Chemists routinely use visual representations to investigate relationships and move between the observable, physical level and the invisible particulate level (Kozma et al., 2002). Generating explanations in a visual format may be a particularly useful learning tool for this domain.

In Experiment 2, participants were asked to create explanations after viewing a recorded class lesson on chemical bonding. The lesson presented information in several different formats: lecture, text, and diagrams. Scores on an immediate post-test were used to confirm that the visual and verbal groups were equivalent prior to the generation of explanations. Following the immediate post-test, participants were asked to explain the process of chemical bonding in either a visual or verbal format. Like Experiment 1, participants were also administered the MRT as a measure of spatial ability. Understanding was measured by performance on a delayed post-test containing both multiple choice and free-response items. Visual explanations demand completeness, so they were predicted to include more information than verbal explanations,
particularly structural information. The inclusion of functional information should lead to better performance on the post-test since understanding how and why atoms bond is crucial to understanding the process. Participants with high spatial ability may be better able to explain function since the sub-microscopic nature of bonding requires mentally imagining invisible particles and how they interact.

4.2 Method

4.2.1 Participants

Participants were 126 8th grade students, ages 13-14, enrolled in an independent school in New York City. Of the 126 students, 58 were females, and 68 were males. Written parental consent was obtained by means of signed informed consent forms.

4.2.2 Design

Each participant was randomly assigned to either the visual or verbal condition. Following the viewing of a brief video lesson on bonding, (13 minutes, 22 seconds), all participants completed the 10-question immediate post-test. Then, sixty-three participants in the visual condition were asked to explain the process of chemical bonding by drawing, and sixty-three participants were asked to explain the process in words. All participants were then administered a 10-question delayed post-test following the completion of their explanations. All participants were administered the Vandenberg-Kuse Mental Rotation Test (MRT) as a measure of spatial ability.
4.2.3 Materials

The materials consisted of the MRT (same as Experiment 1) the video lesson on bonding, two versions of the instructions, the immediate post-test, the delayed post-test, and a blank page for the explanations. All paper materials were typed on 8.5 x 11 sheets of paper.

The video lesson was 13 minutes, 22 seconds long. It began with a brief review of atoms and their structure, and introduced the idea that atoms combine to form molecules. Next, the lesson discussed how location in the periodic table affects behavior and reactivity of atoms, and makes atoms more or less likely to gain, lose, or share electrons. Examples of atoms, their valence shell structure, stability, charges, transfer and sharing of electrons, and the formation of ionic, covalent, and polar covalent bonds were discussed. The example of NaCl was used to illustrate ionic bonding, and the examples of O\(_2\) and H\(_2\)O was used to illustrate covalent bonding. Information was presented verbally, accompanied by drawings, written notes of keywords and terms, and a color-coded periodic table.

The immediate post-test and delayed post-test each consisted of seven multiple choice items and three free-response items (see Appendix A for the complete tests).

The following are example questions from the immediate post-test:

1. The electrons in a nonpolar covalent bond are
   a) shared equally
   b) shared unequally
   c) gained
   d) transferred

6. What type of bonds are formed in N\(_2\)O\(_4\)?
   a) ionic
   b) polar covalent
   c) non-polar covalent
   d) metallic
7. An atom becomes a positive ion when it
a) is attracted to all nearby atoms
b) gains an electron from another atom
c) loses an electron to another atom
d) shares an electron with another atom

8. Is Silicon Dioxide an example of ionic or covalent bonding? Explain.

The following are examples from the delayed post-test:

1. What happens in a polar covalent bond?
   a) electrons are exchanged
   b) electrons are shared equally
   c) electrons are shared unequally
   d) protons are shared

7. What types of bonds are in CO\textsubscript{2}?
   a) ionic
   b) polar covalent
   c) non-polar covalent
   d) metallic

10. What would happen if lithium and fluorine and were combined chemically with each other?

4.2.4 Procedure

The experiment was conducted over the course of three non-consecutive days during the normal school day in the participants’ science classrooms during regularly scheduled class time. On the first day, participants completed the Vandenburg-Kuse Mental Rotation Test as a whole-class activity. Participants without parental consent worked quietly at their desks. First,
participants were given the packet containing the MRT and instructions. Participants were read aloud the instructions and were also instructed to read silently as the directions were being read. Next, they were given untimed practice on several items to be sure they understood the task. Participants were given three minutes to complete items 1-10, and an additional three minutes to complete items 11-20.

On the second day, participants viewed a recorded lesson (13 minutes, 22 seconds) on chemical bonding. They were instructed to pay close attention to the material but were not allowed to take notes on material presented in the video. Immediately following the video, participants were administered the immediate post-test of chemical bonding knowledge. Participants were given twenty minutes to complete the test; all participants finished within this time frame. The pre-test was administered as a whole-class activity. Participants without parental consent worked quietly at their desks during the twenty minutes of testing.

On the third day, the 126 participants were randomly assigned to either the visual or the verbal condition, yielding 63 participants in each condition. The typed instructions were given to participants along with a blank 8 ½ x 11 sheet of paper for their explanations. The instructions differed for each condition:

Visual Condition:
"You have just finished learning about chemical bonding. On the next piece of paper, **draw** an explanation of how atoms bond and how ionic and covalent bonds differ. Draw your explanation so that another student your age who has never studied this topic will be able to understand it. Be as clear and complete as possible, and remember to use pictures/diagrams only. After you complete your explanation, you will be asked to answer a series of questions about bonding."
Verbal condition:
"You have just finished learning about chemical bonding. On the next piece of paper, write an explanation of how atoms bond and how ionic and covalent bonds differ. Write your explanation so that another student your age who has never studied this topic will be able to understand it. Be as clear and complete as possible. After you complete your explanation, you will be asked to answer a series of questions about bonding."

Participants were instructed to read the instructions carefully before beginning the task. The participants completed their explanations as a whole-class activity. Again, participants without parental consent worked quietly at their desks. Participants were given unlimited time to complete their explanations. Upon completion of their explanations, participants were asked to complete the 10 question post-test and were given a maximum of twenty minutes to do so. All participants completed their explanations as well as the post-test during the 45-minute class period.

4.3 Coding

Explanations were coded for structural and functional content, arrows, specific examples, and multiple representations.

4.3.1 Coding System for Structure and Function

A subset of the explanations (20%) were coded by both the author and a middle school science teacher with expertise in Chemistry. Both scorers used the same coding system as a
guide. The percentage of agreement between scores was calculated and was found to be above 0.90 for all measures. The author then scored the remainder of the explanations.

Visual and verbal explanations were coded for structural and functional components. Table 4-1 and 4-2 list the components that were coded for structure and function, respectively. The presence of each component was scored as one point. Points were totaled for each explanation to yield separate scores for structure and function. The maximum score for structural and functional information for each explanation was five points.

Table 4-1.

*Coding guide for structure.*

<table>
<thead>
<tr>
<th>Structural Components (1 pt. each)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms with the correct number of electrons/valence electrons</td>
</tr>
<tr>
<td>Atoms with the correct charges (magnitude, positive/negative)</td>
</tr>
<tr>
<td>Bond between appropriate elements (i.e. between non-metals for covalent molecules and between a metal and a non-metal for ionic molecules)</td>
</tr>
<tr>
<td>Ionic bonds depicted/described as crystalline structure</td>
</tr>
<tr>
<td>Covalent bonds depicted/described as individual molecules</td>
</tr>
</tbody>
</table>
Table 4-2.

_Coding guide for function._

<table>
<thead>
<tr>
<th>Functional Components (1 pt. each)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer of electrons in ionic bonds</td>
</tr>
<tr>
<td>Sharing between atoms in covalent bonds</td>
</tr>
<tr>
<td>Attraction between ions of opposite charges</td>
</tr>
<tr>
<td>Outcome of bonding shows atoms with stable valence electron shell configurations</td>
</tr>
<tr>
<td>Outcome of bonding shows molecules with overall neutral charge</td>
</tr>
</tbody>
</table>

In the example shown in Figure 4-1, four components were coded for structure: atoms with the correct charges (for Na$^+$ and Cl$^-$), a bond between appropriate elements, ionic bonds depicted/described as crystalline structure, and covalent bonds depicted/described as individual molecules. Three components were coded as function: sharing between atoms in covalent bonds, attraction between ions of opposite charges, and an outcome of bonding showing molecules with an overall neutral charge. If an explanation contained information in both a visual and verbal format, the information was coded and tallied for both formats. For example, Figure 4-1 shows an explanation where “separate molecules” are both described and depicted for covalent bonds.
In the verbal example shown in Figure 4-2, one component was coded for structure: bonding between appropriate elements. Four components were coded as function: transfer of electrons in ionic bonds, sharing between atoms in covalent bonds, and attraction between ions of opposite charges.
4.3.2 Coding System for Arrows

Analysis of visual explanations revealed that arrows were present in 92% of visual explanations. Arrows were often used in visual explanations. The use of arrows in visual explanations was categorized into the use of arrows as labels and the use of arrows to show movement/action. Each use of an arrow or arrows was tallied for each explanation. Figure 4-3 shows one arrow was used to show the movement of an electron, four arrows are used to label
atoms, and one arrow is used as a clarification label of the participants use of circled electrons of different atoms to indicate sharing.

![Diagram of ionic and covalent bonding](image)

Figure 4-3. Example of visual explanation showing the use of arrows.

4.3.3 Coding System for the Use of Specific Examples

Participants often explained the processes of bonding through the use of specific examples of atoms and compounds. If participants are able to accurately apply the rules of bonding to a particular example, this may demonstrate a higher level of understanding of the process. Explanations were coded for the inclusion of specific atoms. Figure 4-4 shows the inclusion of NaCl to illustrate ionic bonding, and the inclusion of CO$_2$ and O$_2$ to illustrate covalent bonding.
4.3.4 Coding System for the Use of Multiple Representations

Explanations often contained multiple representations of bonding. For example, ionic bonding and its properties can be represented at the level of individual atoms, or at the level of many atoms bonded together in a crystalline compound, as shown in Figure 4-5. The representations that were coded were as follows: symbolic (e.g. NaCl), atomic (showing structure of atom(s), and macroscopic (visible).
Although there were too few examples to be included in the statistical analyses, some participants in the visual group created “creative” explanations that used metaphors and/or analogies to illustrate the differences between the types of bonding. For example, Figure 4-4 uses two stick figures to show “transfer” and “sharing” of an object between people. The example in Figure 4-6 uses two sharks to represent sodium and chlorine, and the transfer of fish instead of electrons.
Figure 4-6. Example of “creative” visual explanation.
4.4 Results

4.4.1 Spatial Ability

Similar to Experiment 1, participants’ scores on the MRT were used to divide students into low and high spatial participants based on a median split in the data. Scores on the MRT range from 0-20; the mean score for participants was 10.39, and the median was 11. Scores were significantly higher for males (M = 12.5, SD = 4.8) than for females (M = 8.0, SD = 4.9), F(1, 125) = 24.49, p<.01. Males and females were equally distributed across groups.

4.4.2 Structure and Function

The total number of structural and functional information contained in both types of explanations is shown in Table 4-3 and Figure 4-7. The maximum score for structural and functional information for each explanation was five points. Visual explanations contained a significantly greater number of structural components (M = 2.81, SD = 1.56) than verbal explanations (M = 1.30, 1.62 = 1.54), F(1, 125) = 13.69, p<.05, while there was no significant difference in the number of functional components.

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>Visual</th>
<th>Verbal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Structure</td>
<td>2.81</td>
<td>1.56</td>
</tr>
<tr>
<td>Function</td>
<td>2.23</td>
<td>1.06</td>
</tr>
</tbody>
</table>
Many visual explanations contained verbal components (42%) thus the explanations were coded for the structural and functional in information contained in pictures and words. None of the verbal explanations included pictures. Figure 4-8 shows the amount of structural and functional information presented in words and pictures in visual explanations. Structural information was more likely to be depicted in pictures ($M = 3.38$, $SD = 1.49$) than described in words ($M = .429$, $SD = 1.03$), $F(1, 62) = 21.49$, $p<.05$, but functional information was equally likely to be expressed in pictures ($M = 1.86$, $SD = 1.10$) and words ($M = 1.71$, $SD = 1.87$). Functional information in words added to visual explanations significantly predicted scores on the post-test, $F(1, 62) = 21.603$, $p<.01$. 

Figure 4-7. Number of structural and functional units in visual and verbal explanations of chemical bonding.
As in Experiment 1, there were no significant differences in the amount of structural information contained in explanations created by low and high spatial ability participants, see Figure 4-9. However, explanations created by high spatial participants contained significantly more functional components, F(1, 125) = 7.13, p<.05.
4.4.3 **Arrows**

Analysis of visual explanations revealed that 83% contained arrows. The use of arrows in visual explanations was categorized into the use of arrows as labels and the use of arrows to show the movement of electrons and atoms, see Figure 4-10. Each use of an arrow or arrows was tallied for each explanation. There were no significant differences in the use of arrows between low and high spatial participants. The use of arrows as labels ranged from 0 to 4, (M=.19, SD=.60) and the use of arrows to show movement ranged from 0 to 2, (M=.43, SD =.49). The use of arrows was positively correlated with scores on the post-test, r=.293, p<.05. Arrows were used to label atoms and to specify particular types of bonding. They were also used to clarify
explanations by describing action in words and using an arrow to point to the location of the action.

![Bar chart showing mean number of arrows used to label and show movement.]

Figure 4-10. Mean number of arrows used to label and show movement.

4.4.4 Use of Specific Examples

Specific examples of actual molecules and compounds were included in 80% of the explanations. High spatial participants (M = 1.6, SD = .69) used specific examples in their explanations more often than low spatial participants (M = 1.07, SD = .79). The difference was marginally significant, F (1,125) = 3.65, p=.06. There were no significant differences in the use of specific examples between visual and verbal groups. The inclusion of a specific example was positively correlated with scores on the delayed post-test, r=.555, p<.05.
4.4.5 Use of Multiple Representations

Multiple representations were included in 65% of the explanations. Participants generated significantly more when creating visual explanations (M = 1.79, SD = 1.20) compared to verbal explanations (M = 1.33, SD = .48), F (125) = 6.03, p<.05. However, the use of multiple representations did not significantly correlate with delayed post-test scores.

4.4.6 Learning Outcomes

The immediate post-test was scored so that the maximum score was ten points. Each of the seven multiple choice questions and three free-response questions was given one point for the correct answer. The mean score (defined by proportion correct) on the immediate post-test was .463, SD = .469. Scores did not differ significantly between participants in the visual group (M = .486, SD = .308) and the verbal group (M = .443, SD = .260), F(1, 125) = .740, p>.05. Scores between high spatial (M = .532, SD = .421) and low spatial participants (M = .402, SD = .390) also did not differ significantly, F(1, 125) = 2.72, p>.05.

The mean score on the delayed post-test (after participants generated explanations) was .704, SD = .299. Participants in the visual group improved significantly from the immediate post-test (M = .822, SD = .208), F(1, 125) = 51.24, p<.01, Cohen’s d = 1.27. Participants in the verbal group also showed significant increases from the immediate post-test (M = .631, SD = .273), F(1,125) = 15.796, p<.05, Cohen’s d = .71.

A comparison of the delayed post-test scores between groups found significant differences. Figure 4-10 shows scores on the post-test by group and spatial ability. Figure 4-11 shows the scores (defined by proportion correct) on the post-test for participants in the visual and verbal groups. Participants generating visual explanations (M = .822, SD = .208) scored higher
on the post-test than participants generating verbal explanations (M = .631, SD = .273), F(1, 125) = 19.707, p<.01, Cohen’s $d=.88$. In addition, high spatial participants (M = .824, SD = .273) scored significantly higher than low spatial participants (M=.636, SD = .207), F(1, 125) = 19.94, p<.01, Cohen’s $d=.87$ (Figure 4-12). The results of the test of the interaction between group and spatial ability was not significant. A separate analysis comparing performance on multiple choice questions and free response questions did not show any differences between visual and verbal groups or between low and high spatial ability groups.

![Figure 4-11. Scores on the delayed post-test, by group and spatial ability.](image)
Figure 4-12. Scores on the delayed post-test by group.

Figure 4-13. Scores on the delayed post-test by spatial ability.
4.5 Discussion

Experiment 2 was designed to explore the utility of generated explanations in a sub-microscopic content area: chemical bonding. The results supported those of Experiment 1: learner-generated visual explanations provided an advantage over learner-generated verbal explanations. Visual explanations resulted in higher scores on the post-test for both low spatial and high spatial participants.

Visual explanations were likely a successful tool for several reasons. An analysis of the content of the explanations revealed that visual explanations contained a greater amount of structural information (the same finding emerged in Experiment 1). This is not surprising, as structure involves parts and their locations, things very suited to a visual format. Visual explanations were also more likely to include multiple representations, such as a drawing of atoms with their electrons as well as the chemical formula for a compound.

Visual explanations also frequently contained text. An analysis of what was contained in pictures and what was described in text revealed that when text was added, it most often served to explain and clarify function. Structural descriptions in words were rarely added to visual explanations. Additionally, functional information in words added to visual explanations significantly predicted scores on the delayed post-test. This is not surprising, as functional information may be harder to draw in pictures, but may easily be explained in text that augments pictures already constructed. In these explanations, words were used to clarify, extend, and complete the explanation.

No difference was found between low and high spatial participants in the amount of structural information contained in the explanations, but high spatial participants included more function, were more likely to use specific examples, and scored higher on the delayed post-test.
Learning the concepts of chemical bonding, manipulating the information, and mentally imagining atoms, electrons, and the molecules they form requires spatial thinking. While participants were presented with text and pictures during the recorded class lecture, they were not shown, nor did they interact with a physical model as they did in Experiment 1. There are many different types of “hands-on” models used to teach molecular structure and bonding; a revision to Experiment 2 would benefit from exploring the extent to which additional models might aid in the creation of effective explanations.

An interesting finding of Experiment 2 was that the use of arrows significantly correlated with scores on the delayed post-test. How does their use lead to greater understanding? Arrows were most often used to label structure, or to label an action. They were also used to differentiate an initial versus and ending state, to show change. Previous research has shown arrows to serve a number of purposes. Notably, studies have shown the addition of arrows able to convey functional information in a structural diagram (Heiser & Tversky, 2006). While the purpose of this study was to examine student-generated explanations, these results support those of previous work that shows when arrows are used in diagrams in a way that encourages the development of mental models, they become more effective.

Visual explanations in this area of science encouraged the use of an example to show what happens during bonding. A verbal explanation can describe in general what happens, but the explanations can easily resemble that of a surface-level definition. This is much harder to do in a visual format where a learner is forced to choose exactly what an atom should look like. The use of specific examples significantly correlated with scores on the delayed post-test. High spatial participants were more likely to use specific examples when explaining; they may have been better able to develop mental models of bonding.
CHAPTER 5

DISCUSSION

5.1 Introduction

The purpose of this research was to examine how learner-generated explanations, particularly visual explanations, can be used to increase understanding in scientific domains that contain “invisible” components. It was proposed that visual explanations would be more effective than verbal explanations because they are complete, more explicit, and often multimodal. Setting aside the variations between the two studies, the hypotheses of the research were as follows: visual explanations would contain greater amounts of information, particularly information pertaining to structure, functional information would be more likely to occur in words, the content of the explanations would be linked to learning (as measured by post-tests), and success in learning from generating explanations would be mediated by spatial ability. These two experiments differ meaningfully from previous studies in that the information selected for drawing was not taken from a written text, but from a physical object (bicycle pump) and a class lesson with multiple representations (chemical bonding).

5.2 Summary of Significant Findings

Learner-generated explanations were analyzed in two domains. In Experiment 1, participants learned about a mechanical system. Understanding its function depended on understanding the presence and function of hidden structural components, and participants were able to hold and interact with an actual pump prior to generating explanations. The content of Experiment 2, chemical bonding, was invisible due to its scale, and information that students
could use to construct their explanations was presented to them in the format of a recorded class lesson that included both visual and verbal types of information.

Analysis of the content of the explanations found that visual explanations in both domains contained significantly greater amounts of information on structure, however functional components were equally likely to be found in visual and verbal explanations. Visual explanations of the bike pump often featured added text; structure and function was equally likely to be found in words and pictures due to this added text. Visual explanations of the bike pump resulted in greater learning for participants with low spatial ability, but high spatial ability participants learned equally well from generating visual or verbal explanations. Visual explanations were more likely to include essential features, and were more likely to include an important invisible feature, the inlet valve, as well as the movement of air. The inclusion of invisible parts and the use of multiple steps were associated with higher post-test scores, however the presence of arrows was not. In Experiment 1, low spatial ability learners were able to learn as successfully as high ability learners when they explained in a visual format, thereby eliminating any disadvantages low spatial ability participants had performing this type of task. It is possible that high spatial participants were able to learn equally well from either format, however an alternative explanation is that high spatial learners were better able to learn effectively from the pump itself.

In Experiment 2, visual explanations also frequently included added text, however the results showed that this text was more likely to describe function. In the visual explanations of bonding, structure was more likely to be in pictures, and function was equally likely to be found in words and pictures. Visual explanations of bonding resulted in greater learning for participants of both high and low spatial ability, although the scores of high spatial participants were greater
than those of low spatial participants. Unlike Experiment 1, the use of arrows significantly correlated with post-test scores. Visual explanations also contained more multiple representations than verbal explanations. A final significant finding showed that written descriptions of function enhanced drawn visual explanations, leading to higher post-test scores. The results are in line with a dual-coding theory of multimedia learning: meaningful learning requires building connections between visual and verbal representations in the development of a mental model (Mayer, 2005).

5.3 Role of Spatial Ability

Analysis of the content of the explanations found no differences in the structural content produced by participants of low and high spatial ability in either domain. Low and high spatial ability participants explaining the bike pump also did not differ on structural questions on the delayed post-test (low spatial ability participants scored significantly lower on functional questions if they wrote verbal explanations instead of visual explanations). Spatial ability also failed to show an effect on the inclusion of essential features, the inclusion of invisible parts, the use of arrows, or the use of multiple steps in bike pump explanations. Explanations of bonding found that high spatial participants included more functional information and used more specific examples. Participants with high spatial ability may be better able to imagine the movement of structures (both visible and invisible/hidden) (e.g. Hegarty, 1992). In addition, some evidence exists that high spatial participants understand and depict more dynamic, functional info (e.g. Heiser & Tversky, unpublished). It is also possible that high spatial ability participants are better able to hold visual representations in working memory (Hegarty & Just, 1993). These results are in line with those of Hegary & Steinhoff (1997) who found that low spatial ability participants
performed better when they were able to make notes on diagrams, however note-taking had no effect on the performance of high spatial ability participants. The material to be learned in their study were mechanical systems: gear and pulley problems. Finally, these experiments replicate that of previous studies (e.g. Hegarty & Sims, 1994) who have shown that spatial visualization ability is related to the ability to infer the motion of components in a system from a diagram.

Because much of the research on spatial abilities has investigated individual differences, it may be easy to overlook the fact that all students possess spatial abilities. No matter their spatial ability, all humans have the ability to externalize information. Drawing is a cognitive tool that allows students to externalize their thoughts. Experiment 1 showed that visual explanations were helpful only for low spatial participants. In Experiment 2, visual explanations were helpful for both low and high spatial participants. It is likely a mistake to assume that low and high spatial learners will remain that way; there is evidence that spatial ability develops with experience (Baenninger & Newcombe, 1989). It is possible that low spatial participants need more support in constructing explanations that require imagining the movement and manipulation of objects in space.

Since spatial thinking involves mentally imagining and moving objects, creating visual explanations of scientific phenomena may be one way to develop this ability, thereby increasing the effectiveness of these explanations as spatial ability increases. Instruction and modeling of the creation of these explanations is likely crucial. Low spatial ability students may need more support in the generation of explanations, perhaps with examples, rubrics or guides with specific procedural instructions.
5.4 Benefits of Learner-generated Explanations

When students are actively engaged with representations of their own creation, they may be more motivated to learn. There is no doubt that motivation to learn is an important factor controlling the success of any learning strategy, and drawing is likely to engage learners and increase their level of involvement in the task. This understanding may be one way to explain the creation of “creative” explanations by participants in the visual group, but not the verbal group. Mayer (1993) argues that when material is more interesting, students select more information for active processing. In order to generate an explanation, students need to be able to access and gather relevant information from a source. Indeed, the individuality that the construction of visual explanations allows may permit learners to feel a sense of pride in their explanation in a way that a written explanation does not (words are categorically more limited than drawing). Bonding encouraged abstractions, creative, metaphorical explanations. Learners in the two experiments spontaneously added verbal components to visual explanations, and this process did not require explicit instruction.

Generating an explanation involves the recall of critical information and its synthesis of connections between components and their function. The instructions to participants were very open-ended, and research suggests that on open-ended tasks, retrieval practice helps learners to organize information into a coherent knowledge base, and can even help learners later retrieve related information. In other words, the act of retrieving information from memory can make the material more memorable and can lead to better performance on a later test (e.g. Wheeler & Roediger, 1992; Roediger & Karpicke, 2006). There is also some evidence that an increase in performance, hypermnesia, is greater for visual stimuli than words (Erdelyi & Becker, 1974).
5.5 Benefits of Learner-generated Visual Explanations

The visual-spatial nature of drawing matches that of the visual-spatial nature of science learning. This feature encourages learners to monitor, integrate, and regulate as they draw to create a complete representation. It may also be easier for them to detect gaps in their understanding (Novak & Musonda, 1991). The results found in the two experiments are in accordance with Cox (1999) who compared self-constructed diagrams to provided diagrams. He argues that because diagrams provide salient feedback, mistakes become prominent, and this encourages learners to reexamine their understanding and integrate as yet unrelated pieces of information. Through drawing, learners are not only able to see what they are thinking, they are also able to play around with and transform their ideas. One of the great strengths of drawing lies in its ability to immediately reflect back to the creator the ideas that are revealed. This attribute is perhaps why young children find drawing such an attractive and powerful tool for learning. It is immediately holistic and interactive in ways that writing is not. Visual explanations encourage completeness and limit interpretations. The information contained in them is immediately perceptually available and makes explicit the size, shape, and location of objects in a system or process.

Visual explanations may also be more effective than verbal explanations because they require more construction. Cook & Mayer (1988) suggest that verbal explanations support rote learning, while the construction of accurate visual representations requires, and thus supports, deep understanding. Active construction requires learners to become aware of the specific elements and to learn to organize their knowledge in new ways and link to other content (Stern, 2003). Stern et al. (2003) studied spontaneous use of diagrams and found that it was rare, and
even diagram use was accompanied by words. Finally, previous research has shown that learners who were required to actively text and visual information from split sources learned better than those who were given stimuli that were already integrated for them (Bodemer et al., 2004). These results are in line with those of Experiments 1 and 2, which found that while the spontaneous addition of text to visual explanations was common, spontaneous addition of visual representations to text was extremely rare.

As previously mentioned, a learner-generated visual explanation matches the visual nature of the physical bike pump in a way that verbal explanations do not. This similarity may have advantages, but other researchers (e.g. Ainsworth, Bibby, & Wood, 2002) have suggested that learning across modalities results in the greatest understanding because learners must build referential connections between visual and verbal modes. Experiments 1 and 2 both showed that learners spontaneously add text to complement and clarify their drawings; this combination and integration of visual and verbal information may result in the development of greater understanding.

Of course, other researchers have previously discussed a significant issue with visual representations in science: the difficulty in depicting a dynamic process or function. Although effective notations, such as arrows, have been noted, language still possesses advantages in being able to provide descriptions that are specific and precise. However, even without any specific instruction, learners used a variety of devices to convey meaning. Arrows were to label structure (parts) and also to label actions. The meaning of arrows was also often clarified in a key i.e. direction of the flow of air. Arrows have been shown to be a useful tool in generating diagrams, as they can be used for a variety of purposes, including change over time, movement, force, sequence, and causality in diagrams (e.g. Tversky et al., 2000). Arrows can make connections
between pieces of information, but the relationship is asymmetric. The movement of air is obviously essential to the function of the pump. In visual explanations, air was depicted in many ways, including blobs, straight and curvy lines, and dots.

Learning in science is often a “hands on” experience similar to the experience of participants in Experiment 1. Most experimental studies examining learning gains from drawing have asked participants to draw after reading and/or learning from text. If science lessons and learning focus on learning through physical experiences, labs, and models, then taking that information and using it to generate a visual explanation may be particularly useful.

Several researchers, notably Ainsworth et al. (2011) have advocated for drawing to take on a more significant role in science classrooms, to enhance engagement, to learn to represent knowledge, to reason, to communicate, and as a learning strategy. She advocates that drawing can be an effective strategy because drawing one’s understanding requires learners to make that understanding explicit in an reviewable form. Stenning & Oberlander (1995) argue that text permits expression of ambiguity in a way that visuals cannot; their very nature forces their content to be specific. This specificity may also promote the development of causal explanations. Including specific information is easier with visuals: size, color, shape, relations, are all clear and do not need to be inferred. Scaife & Rogers (1996) argue that visual representations are useful for an additional few reasons: computational off-loading, re-representation, and graphical constraining. The development of mental models is often encouraged because information needs to be translated from one form to another, into a representation that captures the key features of a concept or process.

In addition to learning, these findings suggest visual explanations may also be utilized a teaching tool. When accompanied by teacher feedback, student-generated visual explanations
may provide unique opportunities for reflection and revision, and may be a powerful instructional approach. In these experiments, the instructions provided little guidance and no training or examples in how to construct explanations. Thus, the learning effects of generating visual explanations could be even greater, if students were given opportunities to revise their explanations.

If constructing a visual explanation increases learning, how can students be encouraged to do so spontaneously? As noted in the introduction, students are generally presented with diagrams or highly specific illustrations. Even more, they often merely serve illustrative purposes, not as “tools for thinking.” As students move through the elementary grades and beyond, they are given systematic instruction on the use of verbal strategies in representing and understanding information, from underlining in a text, note-taking from a lecture, identifying keywords, and making flashcards. These strategies become familiar, and students thus rely on them instead of incorporating visual strategies. The participants in these studies, like many middle school science students, were often presented with visual representations in learning new content, but were probably asked to generate their own visual representations much less often. In these experiments, generating visual representations was more successful than writing, and this occurred without any formal training. While text was often added to drawings in visual explanations, the reverse was not true. Why are learners less likely to add visual information? Wright et al. (1995) found that while providing way-finding directions, participants rarely included a sketch, even when most of them were able to draw accurate sketch maps. However, participants rated directions that included a visual aid as more useful than ones that consisted purely of text. The authors suggest that the bias towards providing written directions is due to the participants’ reliance on their familiarity with speech. In a problem solving study, Schwartz &
Martin (2004) found that adolescents were reluctant to spontaneously construct visualizations to solve problems and very few did so. However, with encouragement, and realizing the advantages and positive impact of constructing visualizations, students began to construct their own visualizations. Based on these results, it is suggested that instruction in schools explicitly model and teach students how to organize and represent information by drawing. In addition to helping students construct understanding, students’ visual explanations manifest their understanding and their misconceptions, which provide their teachers with access to their levels of understanding.

5.6 Limitations of the Experiments

Limitations of the two experiments influence their generalizability. First, the material learned is explanatory; it reveals how a system works. More research is needed to determine whether visual explanations would be as effective if the material to be learned was a description of unrelated facts, or if the material was in a content area outside of science. An additional limitation is the dependent measures. The post-tests used in both studies did not examine whether learning gains would persist and would extend to other assessments, such as using the knowledge gained to construct physical models.

The generative activities asked of the participants were of a very basic, or “pure” nature. Participants were provided only with pencil and paper. In addition, the instructions merely asked students to explain, without specific prompts or other external supports, such as a rubric or specific instructions on what to include. Supporting the generation of visual explanations by guiding their construction may make them even more useful. Indeed, experimental instructions to learners that direct their attention to structural parts and their role in a system may help them to understand essential features of a system (Alesandrini, 1981). Supports that allow learners to
check the accuracy of their constructed explanations, perhaps by comparing with peers, may also increase their utility (e.g. Van Meter, 2001). Sharing their own explanations with classmates, or co-constructing explanations with another student, may provide students with additional opportunities to restructure their own understanding.

When learners are able to create visual representations of their ideas they may be able to work at a metacognitive level. Van Meter (2001) found that participants who drew engaged in more self-monitoring events relative to non-drawing participants and as drawing support increased, the number of detected and corrected comprehension errors increased. Van Meter & Garner (2005) suggest that without support, the learner may not know how and what to draw if merely instructed to do so, and that these instructions may actually increase awareness of confusion and little else.

Since Experiment 1 lacked an immediate post--test following the examination of the pump, but prior to the creation of the explanation, it is possible that participants learned only from interacting with the pump. In Experiment 2, an immediate post-test following viewing of the recorded class lesson was implemented to allow for the examination of learning due to the generation of explanations. Here, a difference was seen in both low and high spatial participants. When content is easy for the learner, the explanations created may be a direct reflection of accurate comprehension. When content is more challenging, generating explanations may facilitate comprehension and learning.

One variable which is not investigated in this study but may be a factor is the participants’ time spent on the task; there was no time limit imposed on creating the explanations. Additionally, some students may not feel comfortable with their artistic skill, and
so may restrain themselves. These two limitations are related in that they both are a product of generating a representation for submission, rather than for one’s own learning.

Further, the effect of the use of learner-generated visual explanations may be limited to middle school students. Further research should explore the usefulness of this strategy in elementary, high school, and even college classrooms. Results could differ in other areas of science, but even in two very different areas, where the content contains invisible features, learner-generated visual explanations were an effective learning tool.

5.7 Future Studies

The present research also invites additional questions. One area of future research with a lot of potential is how technology may play a role in the construction of explanations. Students can draw what they see in complex visualizations, or create their own visualizations/animations. Teachers and students may face particular challenges when utilizing technology, such as how to incorporate drawings into digital science notebooks and student/classroom websites. Cifuentes & Hsieh (2004) found that both paper and pencil and computer visualization formats were equally successful learning tools compared to a control when learners constructed concept maps. A disadvantage of the use of computers is that learners will need some training in how to use computer-based visualization tools.

Research also may reveal differences in generating explanations in other domains, where drawing may be prohibitively difficult. It may also be necessary to consider the importance of post-tests that are sensitive to the effects of learner-generated drawing. Since this strategy aims to encourage learners’ development of mental models through active construction, post-tests need to be designed to match this higher-order knowledge (Van Meter & Garner, 2005).
Developing coding systems for analyzing free-recall, rather than true-false or multiple choice questions, may reveal this type of deep understanding.

Finally, the addition of verbal information to visual explanations should be explored in further research. In Experiment 2, functional information in words added to visual explanations predicted post-test scores. Greater understanding may come from integrating information from multiple modalities. Aleven & Koedinger (2002) argue that integrating visual and verbal knowledge may help self-explanations to become particularly beneficial. Again, the results are in line with a dual-coding theory of multimedia learning (Mayer, 2005). Learning by generating explanations may also be useful when students can add their own verbal explanations to provided diagrams, or when students construct pictures to accompany provided text.

Current models of science education emphasize constructivism, inquiry, and prioritizing the role of the learner in developing understanding. Students studying science should be, as much as possible, doing what scientists do. In a constructivist approach, knowledge has to be constructed individually by the learner through his or her active engagement with the physical and/or social environment (Roth, 1993). Most practices in science classrooms involve students using verbal formats to construct and revise their understanding, by reading, answering questions, listening to lectures, and engaging in discussion. More research is needed to explore how constructivist approaches can be applied to the generation of visual explanations.

Learner-generated visual explanations may be particularly useful in domains where a process is difficult, or impossible to observe. Students must construct mental models, or internal representations, and depict them in an external representation. In a process where spatial information, such as adjacency, is important, visual representations may be particularly useful. The two experiments show that middle school students are able to use information presented in
two different contexts to assimilate and transform the ideas through their drawn explanations. However, the support, time and opportunity for learners to pursue complexity in their drawing also have to be part of the teaching and learning environment.

5.8 Conclusion

In the generation of visual explanations, learners use the information they gather from new material to create internal representations that become richer with the integration of verbal and non-verbal representations, forming a mental model that then informs and direct the creation of visual explanations. Learners with high spatial ability are more adept at forming and manipulating mental images; this may make the generation of visual explanations easier for them. Learners with low spatial ability may find the task difficult, but may be able to be more successful with generating visual explanations if support is provided.

Together, the results from the two experiments support the use of learner-generated visual explanations as a learning strategy in science. Future studies should explore how this strategy mediates the comprehension of concepts presented in physical models, experiments, and textbooks with performance on learning measures. Students live in a macroscopic world, where objects have mass and occupy space. Understanding “invisible” processes in science, then, presents a challenge. When students are actively engaged in learning activities, they have opportunities to find connections among concepts and negotiate meaning. Generating visual explanations through drawing is likely an underused method of monitoring and supporting students’ understanding of scientific concepts.
REFERENCES


APPENDIX A: POST-TESTS

Experiment 1: Bicycle Tire Pump

**Bicycle Pump**

**True/False Statements**

Instructions: On the line beside each statement, write a “T” if the statement is true or an “F” if the statement is false.

_______ 1. The piston never touches the wall of the cylinder.
_______ 2. Pressure build-up in the cylinder chamber opens the outlet valve.
_______ 3. The piston is attached to the handle.
_______ 4. When the handle is pulled up, the inlet valve opens.
_______ 5. The outlet valve is at the top of the piston.
_______ 6. Air enters the chamber when the handle is pulled up.
_______ 7. The inlet valve closes when the handle is pushed down.
_______ 8. The inlet valve is open when the outlet valve is closed.
_______ 9. The downward movement of the piston causes the inlet valve to close.
_______ 10. The outlet valve is open when the piston is raised.
_______ 11. The outlet valve allows air to enter the chamber.
_______ 12. The pump will not work if the outlet valve stays open.
_______ 13. Next to the handle is the inlet valve.
_______ 14. Next to the hose is the outlet valve.
_______ 15. The outlet valve is in the middle of the chamber.
_______ 16. The inlet valve is inside the piston.
Experiment 2: Chemical Bonding Immediate Post-Test

Instructions: On the line beside each statement, write the letter of the correct answer. For short answer questions, provide a complete and detailed answer.

_______ 1. The electrons in a nonpolar covalent bond are
   e) shared equally
   f) shared unequally
   g) gained
   h) transferred

_______ 2. When Magnesium bonds, how many electrons are gained/lost and what is the charge on the ion that it forms?
   a) loses 2 electrons to form a Mg ion with a 2- charge
   b) gains 2 electrons to form a Mg ion with a 2- charge
   c) loses 2 electrons to form a Mg ion with a 2+ charge
   d) gains 2 electrons to form a Mg ion with a 2+ charge

_______ 3. What is the correct formula for the ion that has 11 protons and 10 electrons?
   a) He
   b) He+
   c) Na+
   d) Na

_______ 4. How many valence electrons does Al have?
   a) 1
   b) 2
   c) 3
   d) 0

_______ 5. How many valence electrons does Li have?
   a) 1
   b) 2
   c) 3
   d) 0
6. What type of bonds are formed in N₂O₄?
   e) ionic
   f) polar covalent
   g) non-polar covalent
   h) metallic

7. An atom becomes a positive ion when it
   a) is attracted to all nearby atoms
   b) gains an electron from another atom
   c) loses an electron to another atom
   d) shares an electron with another atom

8. Is Silicon Dioxide an example of ionic or covalent bonding? Explain.

9. Draw a diagram showing the bond between Calcium and Chlorine.

10. Draw a diagram showing the bond in Br₂
Chemical Bonding Delayed Post-Test

Instructions: On the line beside each statement, write the letter of the correct answer. For short answer questions, provide a complete and detailed answer.

1. What happens in a polar covalent bond?
   e) electrons are exchanged
   f) electrons are shared equally
   g) electrons are shared unequally
   h) protons are shared

2. In the compound NaCl, electrons are
   a) shared equally
   b) shared but not equally
   c) transferred between atoms to form ions
   d) freely moving among the atoms

3. Compounds can be separated by
   a) breaking the atoms into smaller pieces
   b) breaking the bonds between the atoms
   c) using a magnet to attract certain atoms
   d) evaporating the liquid that contains the atoms

4. What part(s) of atoms are involved in bonding?
   a) the whole atom
   b) the nucleus
   c) electrons
   d) protons

5. How many electrons are in the outermost energy level of lithium?
   a) 1
   b) 2
   c) 7
   d) 8

6. How many valence electrons does fluorine have?
   a) 1
   b) 2
   c) 7
   d) 8

7. What types of bonds are in CO₂?
   e) ionic
   f) polar covalent
g) non-polar covalent
h) metallic

8. Draw a diagram showing the bond between Calcium and Fluorine.

9. Draw a diagram showing the bond in $O_2$.

10. What would happen if lithium and fluorine were combined chemically with each other?
Appendix B: Vandenberg & Kuse Mental Rotation Test

Name: _______________________________
Student no: _________________________
Date: ______________________________

1. Your gender
   a) Male
   b) Female
Mental Rotation Test

This is a test of your ability to look at a drawing of a given object and find the same object within a set of dissimilar objects. The only difference between the original object and the chosen object will be that they are presented at different angles. An illustration of this principle is given below where the same single object is given in five different positions. Look at each of them to satisfy yourself that they are only presented at different angles from one another.

Below are two drawings of new objects. They cannot be made to match the above five drawings. Please note that you may not turn over the objects. Satisfy yourself that they are different from the above.

Now let's do some sample problems. For each problem there is a primary object on the far left. You are to determine which two of four objects to the right are the same object given on the far left. In each problem always two of the four drawings are the same object as the one on the left. You are to put Xs in the boxes below the correct ones, and leave the incorrect ones blank. The first sample problem is done for you.

Proceed to the next page
Do the rest of the sample problems yourself. Which two drawings of the four on the right show the same object as the one on the left? There are always two and only two correct answers for each problem. Put an X under the two correct drawings.

Answers:  
(1) first and second drawings are correct  
(2) first and third drawings are correct  
(3) second and third drawings are correct

This test has two parts. You will have 3 minutes for each of the two parts. Each part has two pages. When you have finished Part I, STOP. Please do not go on to Part II until you are asked to do so. Remember: There are always two and only two correct answers for each item.

Work as quickly as you can without sacrificing accuracy. Your score on this test will reflect both the correct and incorrect responses. Therefore, it will not be to your advantage to guess unless you have some idea which choice is correct.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO
PART II

11.

12.

13.

14.
19.

20.

Proceed to the next page

END