INVESTIGATING STUDENT DISCOURSE AND REPRESENTATIONAL UNDERSTANDING IN AN ELECTROCHEISTRY LAB

by

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Math and Science Education
Chemistry Education Concentration

Middle Tennessee State University
December 2023

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ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my committee chair, Dr. Amy Phelps, who continues to support, encourage, and guide me through these long and challenging years. She inspires me not only to be a better chemist but, more importantly, a better chemical educator. Her guidance has been instrumental in the success of this research, and I could not have done this without her.

I would like to express my appreciation to Dr. Jennifer Kaplan, the director of the program, who graciously agreed to be part of my committee member, and who continues to encourage me to keep on moving forward with my writing.

I would like to express my appreciation to Dr. Michael Sanger, my committee member and one of the editors of the *Pedagogic Roles of Animation and Simulations in Chemistry Courses*. This book gave me a deeper understanding of the role of computer simulation in Chemistry learning.

My sincere thanks to two of my committee members, Dr. Ngee Chong and Dr. Keying Ding for their times and their insightful comments.

I would like to thank Dr. Gary White, Dr. Amy Phelps, Dr. Preston MacDougal, and Dr. Keying Ding, who allowed me to work with their students in the CHEM 1120 labs. I would also like to thank Dr. Keying Ding and Dr. Amy Phelps for taking part in these studies.

I would like to thank Dr. Sara Hays, one of my editors, who helped me with reviewing and formatting my dissertation.

Finally, I would like to thank my husband, Paul, for his great support and encouragement over all these years, and for my son Charles, who inspires me to work hard and not give up.

ABSTRACT

Chemistry is considered a difficult subject by most students. Its difficulty lies in Chemistry's complex and abstract nature. This highly abstract nature requires constant interplay and coordination between the macroscopic, particulate, and symbolic representations. Experts can successfully navigate the various representations without overloading their working memory because they can relate their macroscopic observations to the particulate compositions, structures, and properties and express these symbolically. This ability to seamlessly connect the three levels of representations is not intuitive to novices/students. Working with all three representations can lead to cognitive overload as the novice thinks about all three representations independently. The laboratory seems to be the place where students learn to navigate the three levels of representation, and the chemistry department has invested time and money in laboratory courses. This study investigated the types of visualizations, hands-on lab, macroscopic visualization (MV); computer simulation lab, particulate visualization (PV); and hands-on and computer simulation simultaneously, macroscopic and particulate (MPV), that occur during electrochemistry laboratory activity and how each type of visualization influenced students' discourse, interaction, understanding, and connecting the three representations is the main interest. The understanding of what transpires in the laboratory, whom students talked to, what they talked about, and whether the connection between representations occurs during the laboratory activity will help us design a better laboratory activity improve the learning environment for students and justify the cost of running the laboratory.

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CHAPTER 1: INTRODUCTION

Learning chemistry is challenging for many students, and a high percentage of students withdraw, fail, or barely pass their first chemistry course (Chen, 2013; Lamba, 2008; Sjöblom et al., 2016). This situation has become a great concern for many chemistry departments (Hewitt & Seymour, 1990; Johnstone, 2000; Sjöblom et al., 2016), and there is an urgency to find a solution to this problem.

Over a number of years, various organizations such as the National Science Foundation (NSF) and the American Chemical Society (ACS) have recognized the same problems and have devoted time and resources towards finding solutions (Hixson & Sears, 1995; Damkaci et al., 2017). Numerous studies have been done to identify topics with which students have difficulty (De Jong & Treagust, 2002; Duncan & Johnstone, 1973; Finley et al., 1982; Johnston et al., 1977; Kellett & Johnstone, 1974). Others focused on identifying students' misconceptions, such as the misconceptions about the electrochemistry concept (Acar & Tarhan, 2008; Ahtee et al., 2002; Barke et al., 2009; Garnett & Tregust (1992a, 1992b); Lin et al., 2002; Ogude & Bradley, 1994; Sanger & Greenbowe (1997a, 1997b, 2000)). Others focused on learning theories: Piaget's theory of constructivism (Bodner, 1986; Fensham, 1994; Good et al., 1979; Goodstein & Howe, 1978; Herron (1978, 1996); Opara & Waswa, 2013); Ausubel's theory of meaningful learning (Bretz, 2001; Fahmy & Lagowski, 2003), Johnstone's cognitive process of learning, and Johnstone's triangle of representations (Bodner & Domin, 2000; Johnstone (2006, 2009, 2010)) to name a few. All in an effort to improve the learning of chemistry.

Several chemical educators believe we can help students learn chemistry concepts if we make learning meaningful and students are actively involved in the process of learning (Hostein & Lunetta, 2003; Woolnough & Allsop, 1985). Learning in the laboratory is ideal for this (Hofstein & Lunetta, 1982). However, with the increasing cost of running a laboratory program (Reid & Shah, 2007), some chemical educators have started questioning the relevance of laboratory work in freshman-level college chemistry, and some have even considered the possibility of eliminating traditional hands-on laboratory work (Hawkins & Phelps, 2013; Hofstein & Mamlok-Naaman, 2007; Josephsen & Kristensen, 2006) and replaced it with the computer simulation (Hawkins & Phelps, 2013; Josephsen & Kristensen, 2006).

The implementation of computer simulation labs (CSLs) is not new, and several studies using computer-based programs as lab replacements or enhancements were carried out in the 1970s and 1980s (Cavin et al., 1978; Davis et al., 1973). More recently, in the wake of a global pandemic, CSLs have been designed with online or distance education in mind. While these CSLs in many ways are technology-driven regurgitations of the demonstrations from the 1920s and 1930s, they are cost-saving (Dalgarno et al., 2009; Morozov et al., 2004). CSLs are designed with different purposes including helping students feel more confident when they actually visit the laboratory and helping address some conceptual learning problems with chemistry (Dalgarno et al., 2009; Josephsen & Kristensen, 2006; Yaron et al., 2003), CSLs replicates real experiments and giving students opportunities to solve open-ended problems (Cavin et al., 1978; Davis et al., 1973; Dalgarno et al., 2009; Morozov et al., 2004; Yaron et al., 2003). Many CSLs include simulations of experiments and have the potential to lighten the cognitive load for students by displaying the interactions of atoms and molecules at the particulate level. A few researchers claimed that CSLs show an increase in the ability of students to think at the particulate level and connect that to the macroscopic level (Dalgarno et al., 2009), and fewer studies were conducted to test the ability of virtual labs to replace hands-on labs (Josephsen & Kristensen, 2006; Hawkins & Phelps, 2013). Before conclusions can be made about replacing hands-on laboratory activities with virtual ones, more research is needed to understand what transpired during each type of discourse that occurred in this lab setting and whether or not they led to the connection between the macroscopic, particulate, and symbolic levels.

Significance of the Study

With the rising cost of operating chemistry laboratories and the suggestion of eliminating laboratory work in general chemistry, it is more important than ever to take a hard look at the chemistry teaching laboratory and what happens there. Can we implement cost-effective laboratories in the general chemistry course that help students learn chemistry by promoting conceptual understanding? Can introductory laboratories promote meaningful learning and promote students' positive attitudes? Can it all be done within three hours of block time? What really happens in a chemistry teaching lab and is it something we value? To answer these questions, it is essential to have a clear picture of what transpires in each type of laboratory setting (traditional hands-on, CSLs, and the mixture of the two styles). However, few research compared the type of discourses that occurs in each laboratory setting. Whom do students talk to and what do they talk about? What features in each laboratory style do students tend to focus on, and whether or not the lab activity helps students make connections between the macroscopic, particulate, and symbolic representations?

Research Objectives

The first research objective is to gain a better understanding of the role of the laboratory and what is possible for students to learn in that particular laboratory setting. By listening to students' discourses during laboratory activities, finding what features of laboratories students tend to focus on and how they spend their time in the laboratory, and listening to what they talk about and to whom they talk to during the laboratory activity, we should have a better understanding of the connections between the role of laboratory and student learning in chemistry.

Visualization is key to understanding chemistry concepts. The second research objective is to understand better the impact of two different types of laboratory techniques; a traditional hands-on lab where macroscopic visualization (MV) is prominent and a computer simulation where particulate visualization (PV) is prominent on students' learning experiences.

Finally, the answer to the question, "To what extent does the nature of students' discourse promote students' understanding of chemistry across macroscopic, microscopic, and symbolic levels?" will be addressed.

Dissertation Organization

The dissertation consists of five chapters, including the introduction, that are organized as follows:

Chapter 1: Introduction. This chapter provides the Introduction, purpose, significance of the study, and research questions.

Chapter 2: Literature Review: This chapter provides the theoretical frameworks for the study. The focus is on the three main areas of research: problems associated with chemistry learning, visualization and Johnstone's three representations of chemistry, and issues with the learning of electrochemistry.

Chapter 3: Comparing the influence of visualization type in an electrochemistry laboratory on the student discourse: Who do they talk to and what do they say?

Chapter 4: Making Connections: A Qualitative Study of Electrochemistry

Chapter 5: Presents conclusions to this study and provides implications for theory and future research.

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CHAPTER 2: LITERATURE REVIEW

Introduction

Chemistry has always been a learning-by-doing subject (Pickering, 1993), and the laboratory has been an essential part of the process (Johnstone, 1983) because it allows students to experience phenomena firsthand (Hofstein, 2004). Laboratory activities allow students to construct their own understanding of chemistry concepts in a way that lecture or demonstration alone cannot easily accomplish (Bowers, 1924; Bretz, 2019; Bruck & Towns, 2013; Tobin, 1990). The American Chemical Society (ACS) Committee recognized the importance of laboratory courses and required students from ACS' approved institutions to have 400 hours of laboratory work beyond freshman chemistry (Bretz, 2019). However, while the laboratory potentially provides students with opportunities to integrate cognitive, affective, and hands-on learning (Galloway et al., 2015), the cost of running a university laboratory can be substantial, and the effect on students' learning of chemistry remains inconclusive (Hofstein & Lunetta (1982, 2004); Kirschner & Meester, 1988; Lazarowitz & Tamir, 1994; Lunetta, 1998). Despite this, we still hold on to lab as part of the curriculum because we believe that it is worth it regardless of the type of laboratory practices. The opportunity to observe chemical reactions visually, placing a piece of copper in a colorless solution of silver nitrate and watching the solution gradually turn blue, helps students connect to the chemical concepts (Hofstein, 2004) beyond the written word or the chemical equation. With this in mind, the laboratory could still be the ideal place to allow students to engage in meaningful learning while fostering students' positive attitudes (Galloway et al., 2015; Lunetta et al., 2007).

To understand the nature of chemistry, it is important to look at how modern chemistry differs from the days of alchemy, the role of the laboratory in the University environment, and Johnstone's nature of chemistry. To combat students' learning difficulties, researchers looked at how students learned based on Ausubel's learning theory and how it related to Johnstone's information processing model, and finally how visuals influence students' learning.

How Modern Chemistry Differs from the Early One

The modern view of learning chemistry involves the interplay among representations, visible (i.e., macroscopic), invisible (particulate), and symbols, models, and formula (i.e., symbolic) (Chandrasegaran et al., 2007; Johnstone (1991, 1993, 1997); Lin et al., 2016; Ramnarain & Joseph, 2012; Treagust et al., 2000; Tsaparlis, 2009). These three levels of representation did not develop simultaneously but evolved as the field of chemistry grew.

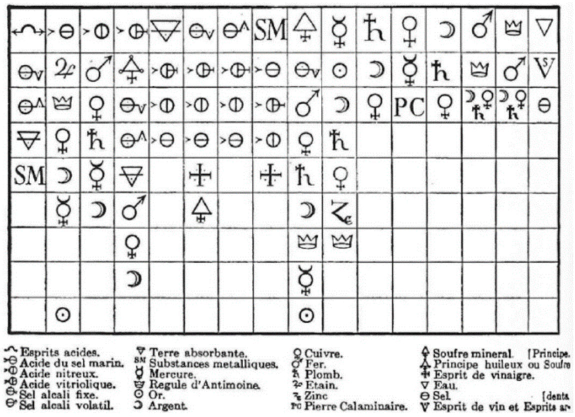
The interplay between macroscopic and symbolic representations in chemistry has existed since Plato's time (C. 42-348BC). The ancient Greeks used symbols in the form of regular polyhedrons to represent matter, macroscopic properties, and the transformation between elements. These polyhedrons are known as Platonic solids. The shape of the polyhedron represents the nature of the elements. For example, the tetrahedron is fire, the octahedron is air, the icosahedron is earth, and the dodecahedron is the cosmos. The length and size represent the elements' macroscopic properties, and polyhedrons with a similar symbol at the vertex mean these elements can transform into one another (Restrepo & Villaveces, 2012). The interplay between macroscopic and symbolic representation in chemistry was also prominent in the practice of alchemy.

Unlike Platonic solid symbols, alchemists used the name of planets and mythological gods or goddesses to represent elements. The Sun represents gold; Moon is silver; Venus is copper; the messenger of the gods, Mercurius is mercury; and Mars is iron (Fabbrizzi, 2008). The age of the alchemists dates back to the time of the Egyptians, around 5000 B.C.E., and lasted until the 16th century. Alchemists were known for their work with metallurgy, attempting to transmute ordinary metals to gold, distilling alcohol, and allegedly producing philosopher's stones that defy death itself. Alchemists were secretive with their work, creating their own nomenclatures and special symbols that served as encrypted instructions passed on to their apprentices (Fabbrizzi, 2008; Krausoff & Beiser, 2017; Martin, 2001; Morris, 2015; Vicens, 2011). Without consensus on the symbolic representations and with some desire to keep work secret, the advances of their trade were known to a few within their circle.

The first attempt to standardize elements' symbolic representation and chemical properties was in the late 15th century. Etienne-François Geoffroy (1672-1731), a French chemist who was inspired by the work of the alchemist’s work (Joly, 2014) invented the "Table des rapports entre les substances chimiques," also known as 'table of affinity' (Figure 1). The table of affinity is the first known table showing the connection between symbolic and macroscopic relationships between elements (Joly, 2014; Restrepo & Villaveces, 2012). The symbols on the first row of the table represent the principal substances. The symbols of the subsequence rows represent other substances that will react with the principal substance in the first row. The closer the substances are to the first row of substances (i.e., the principal substances), the more likely they react with the principal substance. The farther the elements are from the first row, the less likely they will react with them. (Joly, 2014; Restrepo & Villaveces, 2012).

Figure 1

Table of Affinities by Geoffroy 1718



Esprits acides.
Acide du sel marin.
Acide nitreux.
Acide vitriolique.
Sel alcali fixe.
Sel alcali volatil.

▽ Terre absorbante.
SM Substances metalliques.
☿ Mercure.
Regule d'Antimoine.
☉ Or.
☽ Argent.

♀ Cuivre.
♂ Fer.
♄ Plomb.
♃ Etain.
Zinc
PC Pierre Calaminaire.

Soufre mineral. [Principe.
Principe huileux ou Soufre
Esprit de vinaigre.
▽ Eau.
⊖ Sel. [dents
Esprit de vin et Esprits ar-

Note. From "Mathematical Thinking in Chemistry" by G. Restrepo and J. L. Villaveces, 2012 *International Journal of Philosophy of Chemistry,* 18(1), p.9

By the 17th century, the use of planets and mythological gods or goddesses to represent elements was replaced by modern symbols. A Swedish chemist, Jöns Jakob Berzelius (1779-1848), changed the symbols of elements from geometric figures to use the first letter or two of elements' names to represent elements. He also expanded the use of symbols to include graphs, chemical formulas, and chemical equations (Barke et al., 2009; Fabbrini, 2008).

The late 18th century is known as the dawn of modern chemistry (Cracolice & Peters, 2020; Kozma et al., 2000). A group of French chemists led by Antoine Lavoisier (1743-1794) established the new scientific community norms, where experimentation as part of scientific investigation (Cracolice & Peters, 2020; Kozma et al., 2000). He set up a series of experiments that disproved Johann Becher’s phlogiston theory of combustion. Becher and Staht proposed that matter burnt because it contains a phlogiston substance (Cracolice & Peter, 2020). In 1778, Lavoisier set up a series of experiments that disproved the existence of phlogiston and gave rise to a new hypothesis. The new hypothesis states that when a substance burns, it gains weight by combining it with invisible gas, later named oxygen (Morris, 2015). Lavoisier’s experiments were repeated, confirmed, and the results were accepted as the combustion theory (Morris, 2015). Lavoisier's laboratory works became a new norm of scientific practice and initiated the connection between macroscopic views and particulate explanations. Lavoisier also expanded the use of symbols to include mathematical equations. His book, 'Méthode de Nomenclature Chimique' used a new language that showed the strong interplay between mathematical symbols and chemical processes (Restrepo & Villavecca, 2012), and chemists incorporated the particulate nature of substances as part of chemistry writing (Barke et al., 2009; Fabbrini, 2008). In the 19th and 20th centuries, with the development of organic chemistry and the synthetic discoveries of organic compounds, symbols were expanded to include two or three-dimensional structures representing molecules from simple to complex (Barke et al., 2009; Fabbrini, 2008). Symbolic representations evolve as the field of chemistry evolves from alchemy’s practice to modern chemistry.

In modern-day chemistry, the trilevel of representations become a central role in reasoning, communicating, thinking, and facilitating learning within the chemistry community (Chandrasegaran et al., 2007; Johnstone (1991, 1993, 1997); Lin et al., 2016; Ramnarain & Joseph, 2012; Treagust et al., 2000; Tsaparlis, 2009). Experts have years of learning and substantial pre-existing knowledge to help them manipulate these trilevel representations simultaneously without overloading their working memory (WM). On the other hand, novices with inadequate background knowledge cannot easily see the connection between representations and can easily overload their WM when attempting to make the necessary connections (Baddeley, 1990; Taber, 2009). Investigating how these representations are related and how we can help students build connections, reduce WM overload, and reduce students' frustration should lead to better chemical education and prevent students from dropping out of chemistry.

The Role of Laboratory Practice in University Environments

The role of laboratory practice has undergone several transformations, from providing training for the skills chemists needed for industrial work or research during the industrial revolution (Brown, 1932; Carmel et al., 2019; Johnstone, 1993; Reid & Shah, 2007) to confirming and enhancing chemistry principles in the years following World War I (Domin, 1999; Hofstein & Lunetta, 1982), to preparing more scientists for discovery and scientific investigation after 1960 (Johnstone, 1993; Shulman & Tamir, 1973). The role of the chemistry laboratory as part of a natural science component in the United States did not begin until the mid-19th century. In 1842, two professors, Benjamin Silliman, and Eben Horsford, were the first to officially offer chemistry laboratory courses at the University. Dr. Silliman offered a laboratory course at the Yale Scientific School (Brown, 1932). The same year, Dr. Horsford offered a laboratory course at the Lawrence Scientific School, affiliated with Harvard University (Sheppard & Horowitz, 2006). Before that, laboratory courses were not considered University level courses. Students listened to the lectures. Professors illustrated the chemical concepts by performing experiments in front of the lecture hall or their private laboratory (Brown, 1932; Morris, 2015). Students were not permitted to touch laboratory instruments. Laboratory work was reserved for the privileged few students accepted as apprentices or assistants. Other students who wanted to learn laboratory methods of chemical analysis could do so by attending private laboratories (Brown, 1932). There was much resistance to making the laboratory course a part of the university curriculum. Once laboratory courses became part of the natural science curriculum, they gained popularity and expanded to the science curriculum in high school (Sheppard & Horwitz, 2006). One reason for this shift is the influence of constructivist approaches to learning (Nakhleh et al., 2002). This influence can be seen in the call for science educators to develop lab environments to include more opportunities for students to manipulate equipment and construct their knowledge of the scientific concept (Nakhleh et al., 2002). This shift in emphasis to constructivist approaches could be seen in the fact that many educators advocated that the laboratory be more student-focused and inquiry driven than in previous decades of teacher-focused lab directives (Tobin, 1990). This shift to more student-centered approaches continued to grow and led to a focus on laboratory education since the laboratory was the most logical place to incorporate more open-ended, student-centered problem-solving in the form of discovery and inquiry styles of the laboratory (Domin, 1999). These approaches, however, were not easy to implement and an overall review of laboratory instruction showed few improvements (Nakhleh et al., 2002).

Johnstone’s Framework of Trilevel of Representations

Johnstone (1991, 1993, 2000, 2010) claimed the nature of chemistry is highly abstract and requires a constant interplay and coordination between the macroscopic, particulate, and symbolic representations. The macroscopic level represents visible objects that can be observed by normal senses (Treagust et al., 2000). Both the particulate and symbolic levels are abstract. The particulate level represents an abstract concept, the atomic and molecular views (Johnstone (1991, 1993, 1997); Lin et al., 2016). The symbolic level represents chemical symbols, formulas, graphs, molecular drawings, and mathematic equations (Chandrasegaran et al., 2007; Ramnarain & Joseph, 2012). While experts easily navigate between these multiple representations, novices operate primarily at the macroscopic level, which is concrete and visible. Chemical explanations, however, require the ability to visualize the interaction at the particulate level, and many laws and models are expressed in symbolic representations (Gabel, 1999).

Macroscopic Representation. Johnstone (2009) recommended that students start with the macroscopic level before moving on to the particulate level. Introducing chemistry through macroscopic representation is the easiest compared to the other two. Novices are familiar with the macroscopic representation because it is a tangible view. Students could experience macroscopic representation through scientific, personal, and historical aspects (Adams, 2012). Learning in a traditional hands-on laboratory is an example of learning through a scientific aspect (Gabel, 1999; Treagust et al., 2003). Students can see macroscopic changes such as a flash of light, color changes, bubble formation, precipitation appearing, and the substance getting hotter or more relaxed during the chemical reaction. The traditional hands-on activity promotes students' interest (Hodson, 1990). For example, Hunter, Hawkins & Phelps (2019) found that during the electrochemistry activity, students were excited to see the change in the physical appearances of reactants and products. This peer-to-peer discussion, however, only occurred at the macroscopic levels.

Particulate Representation. The particulate representation, while real, is intangible to and unobservable by the five senses and contradicts the everyday views of the learner (Johnstone (1991, 1993, 1997); Lin et al., 2016; Treagust et al., 2003). The particulate view includes atoms, molecules, electrons, bond energy, and inter and intra-molecular forces, which cannot be seen by the naked eye. (Chandrasegaran et al., 2007; Treagust et al., 2003). Because these representations are beyond students' normal senses or experiences, they are difficult for students to comprehend (Gabel et al., 1987), but help explain the macroscopic observations.

In the last decade, many chemical educators have taken advantage of computer software programs to assist students in visualizing the particulate level, for example, The Concord Consortium (htttp://concord.org), The Connected Chemistry Curriculum (www. Connchem.org), PhET Interactive Simulations at the University of Colorado (http://phet.colorado.edu). Computer simulations and animation technology enhanced conceptual understanding (Davidowitz & Chittleborough, 2009) by displaying a detailed view of the atoms and molecules and their interactions at the particulate level (Wu et al., 2001), making abstract concepts fundamental and observable (Suits & Sanger, 2013; Yang et al., 2003). While computer simulation provides students with a concrete view of particulate representations, it lacks observable visual effects and does not guarantee that students form accurate pictures of what occurred at the particulate level (Hunter et al., 2019).

Symbolic Representation. Symbolic representations have undergone several transformations (Fabbrizzi, 2008; Martin, 2001; Morris, 2015; Krausoff & Beiser, 2014; Vicens, 2011; Joly, 2014; Restrepo & Villaveces, 2012) and have expanded to include various forms: chemical nomenclatures, elements' symbol, units of measurements, various measurable quantities, algorithmic relationships, molecular models, graphs, chemical equations, structures, and chemical process (Chandrasegaran et al., 2007; Johnstone (1993, 1997, 2000); Ramnarain & Joseph, 2012; Taber, 2009). While the chemistry community uniformly accepts and understands symbolic representations, it is still a special language with specific rules (Taber, 2009). Experts have years of learning and know the meanings of these types of representations. On the other hand, Novices treat symbolic representations like a second language (Taber, 2009), with little or no pre-existing knowledge to help them interpret their meaning and therefore easily overload their cognitive demand.

Traditional teaching emphasizes an algorithmic approach to solving chemistry problems (Berkel et al., 2009), but without explicitly connecting to the underline concepts (Nakhleh & Mitchell, 1993; Tsaparlis, 2021). As a result, students memorize chemical formulas without conceptual understanding and often plug the number into the wrong formula (Berkel et al., 2009) or invent a non-mathematical strategy of their own (Schmidt, 1994) to solve chemistry problems. The evidence of the disconnection between the algorithmic approach and conceptual understanding is found in several areas of chemistry learning: electrochemistry (Sanger & Greenbowe, 1997), gas law (Nurrenberg & Pickering, 1987), stoichiometry problems (Gabel, 1993; Sawrey, 1990;), and acid-base reactions (Bodner, 1992). In all cases, students can solve problems using an algorithmic approach, but cannot solve problems when presented with different representations (e.g., graph, particulate views, particulate explanations). Many of the misconceptions in electrochemistry are the results of the traditional method of teaching (Lin et al., 2002; Ogude & Bradley, 1994; Sanger & Greenbowe (1997, 2000); Schmidt et al., 2007).

Learning Theory—From Ausubel to Johnstone's Information Processing Model

Preexisting knowledge plays an important role in determining what students learn (Ausubel, 1968). It provides a filter for their attention, helps them decide which new information is selected, and lays a foundation for adequately interpreting observations (Garnet & Treagust, 1992a; Tsaparlis, 2009). Chemists can think micro, particulate, and symbolic simultaneously without overloading their working memory because they have core knowledge of chemistry that help them combine and organize a large amount of information into a single domain and process them in a single chunk of information (Baddeley, 1990; Garnet & Treagust, 1992a; Russell et al., 1997; Taber, 2009). Without pre-existing knowledge of chemistry concepts, students have no mechanism to assimilate or accommodate what they have just learned and what they already know. Students, therefore, learn by rote memory (Herron, 2005). The lack of prior knowledge could be one of the reasons why students perform poorly in chemistry tests (Keig & Rubba, 1993). For example, if students do not know the rule for writing chemical formulas, they won't be able to write the chemical formula correctly even though they saw how atoms are connected (Keig & Rubba, 1993).

The pre-existing knowledge is stored in long-term memory (LTM). The pre-existing knowledge determines what information will pass through the perceptive filter and into the working memory (Baddeley, 1997; Johnstone (1997, 2010)). The working memory (WM)'s functions as a temporary storage and information processing center (Baddeley, 1997; Johnstone (1997, 2010)). WM has limited space. An average person can only hold and process seven chunks of information simultaneously at any given time (Miller, 1956). Since it is a shared space, the more information it holds, the less information can be processed (Reid, 2021). Short-term memory is overloaded above this magic number of seven, and students' processing performance is sharply reduced (Miller, 1956). Johnstone and El-Banna (1986) analyzed students' performance versus the information load of questions. They defined the information load as the maximum number of thought steps and processes to solve problems successfully. They found that, on average, students failed to solve problems if the steps and processes to solve problems were 7 or greater (Johnstone & El-Banna, 1989). Students performed better if the problems required only a single step, but when more pieces of information are added to the problems, the rate of success in solving the problems decreases (Herron, 1996; Johnstone & Kellett, 1980; Lin et al., 2016; Ramnarain & Joseph, 2013). Pre-existing knowledge can improve students’ performance by organizing similar information and processing them as one chunk of information (Johnstone (1997, 2000); Reid, 2021). The more general knowledge anchors in the LTM, the easier the new information can be recognized and processed as a single domain (Kozma, 2003; Russell et al., 1997).

Information overload is one of the keys to students learning difficulty in chemistry (Johnstone & Kellett, 1980; Reid, 2021; Sirhan, 2007; Tasparlis, 2009). Knowing the maximum number of thought steps and processes before students overload their working memory helps chemical education understand the challenges students face when solving problems. With this understanding, they can design a better lesson plan and curriculum.

Virtualization and How It Affects Students' Learning in the Laboratory

Learning chemistry is challenging for many students. Its difficulty lies in the complex and abstract nature of the subject (Gabel, 1998; Johnstone, 2000; Tasker, 2014). While students can observe chemical phenomena visually at the macroscopic level (macroscopic view), the explanation of how and why things react as they do lies at the particulate level (particulate view), and usually, all of this is summarized and expressed using symbolic representations (symbolic view). Visualization is a key to understanding chemistry concepts and has the potential to lighten the cognitive load for students. Consider the situation of teaching oxidation–reduction. Oxidation is defined as the loss of electrons, and reduction is the gain of electrons. We might introduce a macroscopic example like rust to try to tie these definitions to the student's experiences. Then we move to the symbolic treatment of oxidation and reduction by writing half reactions and following the loss and gain of electrons through the steps. Chemists are successful in chemistry because they see the connections between these three levels of representational visualization (i.e., macroscopic, particulate, and symbolic) and move seamlessly from one to the other (Johnstone, 2000; Taber, 2013; Talanquer, 2011) and therefore do not overload their cognitive processes. Students, the novices, treat these three levels of representations as discrete pieces of cognitive material that serve to increase the cognitive load associated with learning chemistry.

There is no doubt that chemists are very interested in the particulate representations of processes, and it is almost impossible to make a connection between the macroscopic level and the particulate level of understanding without some mental image of how particles interact (Deratzou, 2006). Students do not see this connection, and most do not develop it naturally, often creating inaccurate pictures of the particulate matter. Misconceptions found in electrochemistry illustrate this point and are plentiful (e.g., Garnett & Treagust, 1992a; Ogude & Bradley, 1994; Sanger & Greenbowe (1997, 2000)). For example, since students cannot see electrons, some students form an image of electrons floating freely in a solution (Ogude & Bradley, 1994) without any assistance from the ions (Sanger & Greenbowe, 1997). Other students imagine electrons moving through a solution by jumping from one ion to the next (Garnett & Treagust, 1992a) or from one electrode to another (Schmidt et al., 2007). Often students see a circuit being completed within a galvanic cell by electrons flowing from one half-cell solution to the other through the salt bridge (Garnet & Treagust, 1992a). An inability to form an accurate image of what electrons are doing at the particulate level not only impedes students' ability to acquire the correct conceptual understanding (Hamza & Wickman, 2008; Songer & Mintzes,1994; Taber, 1995) but also prevents students from integrating the three level of representation during the process of learning. (Ogude & Bradley, 1994; Sanger & Greenbowe, 1997). Therefore, if students could visualize an accurate particulate model, it would enhance their understanding of the abstract concept (Doymus et al., 2010; Lee & Osman, 2012) and reduce the cognitive load associated with learning chemistry.

In the last decade, many chemical educators have taken advantage of freeware programs, using them in both the lecture and in the laboratory to try to assist students in visualizing the particulate level. Computer simulations offer students an explicit view of the interactions at the particulate (sub-microscopic) level (Kozma et al., 2000; Kozma & Russell, 1997; Wu et al., 2001) and are often used as a pre-lab to prepare students for chemistry laboratory (Krupnova, 2016; Winberg & Berg, 2007), as an alternative to the traditional laboratory for distance learning (Dalgarno et al., 2009; Krupnova, 2016) or as a wholesale replacement of the hands-on laboratory that is much more cost-effective (Hawkins & Phelps, 2013; Tatli & Ayas, 2013). Viewing dynamic two or three-dimensional animations has been shown to help students learn to connect the particulate and the symbolic representations (Williamson & Abraham, 1995). Winberg and Berg (2007) found that students who used the computer simulation visualization in the pre-lab asked more theoretical questions during the laboratory activity than the traditional group. When comparing achievement on a test following laboratory, students using a computer simulation lab and students in a traditional hands-on lab performed equally well (Hawkins & Phelps, 2013; Tatli & Ayas (2012, 2013)). While many studies compare different laboratory techniques with computer simulations, these studies rarely emphasize the type of visualization prominent in each type of laboratory and how it affects the dynamics of students' interactions in the laboratory. In an effort to gain a better understanding of these influences from the students' perspectives while engaging in an electrochemistry laboratory activity, we deployed two different types of laboratory techniques; a traditional hands-on lab where macroscopic visualization (MV) is prominent and a computer simulation where particulate visualization (PV) is prominent. We listened to the students' discourse to better understand the impact each type of visualization had on students' learning experiences.

Summary

The nature of modern chemistry includes macroscopic, particulate, and symbolic representations. Many of the great discoveries and probably future discoveries started because of curiosity about the macroscopic nature of phenomena, but the particulate views of atoms, molecules, ions, and subatomic particles and their interaction are the keys to understanding the macroscopic world (Reid, 2021).

Symbolic representations come in many forms (Taber, 2009). Chemists take advantage of this special language which is normally abbreviated from the full names or full process and recognized by the chemists' community to describe the macroscopic feature or particulate explanations. Chemical education uses some forms of symbolic representations to initiate novices (i.e., students) into the chemistry community. Words or phrases like oxidation, reduction, being oxidized, being reduced, oxidizer, reducer, redox reaction, and half-reaction are common words to chemists, but to novices, they are encrypting codes that must be memorized if they want to learn the trade secret.

It is impossible to learn, read, or perform experimentation without seeing some forms of symbolic representation. Chemical educators emphasize these special languages, which are abstract, in conveying chemistry concepts to students (Gabel, 1999). They used the word like oxidation (i.e., abstract – symbolic representation) and jumped into the explanation in terms of losing electrons (i.e., abstract - particulate representation), then gave an example of iron rusting (i.e., macroscopic representation) and summarized the concept, by writing chemical equation (i.e., abstract – symbolic representation) (Hunter et al., 2019). Students attempt to follow the professor's train of thought by rote memorizing all these new words they never heard of, rote memorizing their definitions that could not be seen, memorizing the example given, and learning the new symbolic representations along with the rule of writing them. They process all these new pieces of information individually, leading to cognitive overload and resigning to the idea that chemistry is difficult.

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CHAPTER 3: COMPARING THE INFLUENCE OF VISUALIZATION TYPE IN AN ELECTROCHEMISTRY LABORATORY ON THE STUDENT DISCOURSE: WHO DO THEY TALK TO AND WHAT DO THEY SAY?

Abstract

A laboratory is a large investment of time and money for departments of chemistry yet discussions continue about its purpose in the educational process. Helping students navigate the three levels of representation; macroscopic, particulate and symbolic is a potential use of this time. This study looked at two different types of visualization for an electrochemistry laboratory in second semester general chemistry and the impact that the visualization type had on the student discourse. Macroscopic visualization (MV) was accomplished through a traditional hands-on laboratory and particulate visualization (PV) was achieved using a computer simulation featuring animated electrons and ions. The type of visualization impacted how much the students talked, who they talked to, and what they talked about. The MV students engaged in less peer-to-peer discussion than the PV students. The MV students expressed more excitement about their observations and were more focused on getting the data quickly. The MV spent most of their time physically doing the laboratory work while spending little time discussing the concepts. The PV students spent more time talking about concepts with their peers especially at the particulate level even answering macroscopic questions with particulate explanations. The type of visualization influenced all aspects of the student discourse.

Introduction

Chemistry has always been a learning by doing subject (Pickering, 1993), and the laboratory has been an essential part of the process (Johnstone, 1983) because it allows students to experience phenomena first hand (Hofstein, 2004). Laboratory activities allow students to construct their own understanding of chemistry concepts in a way that lecture or demonstration alone cannot easily accomplish (Bruck & Towns, 2013; Tobin, 1990). However, while the laboratory potentially provides students with opportunities to integrate cognitive, affective and hands-on learning (Galloway et al., 2015), the cost of running a university laboratory can be substantial, and the affect on students' learning of chemistry remains inconclusive (Hofstein & Lunetta (1982, 2004); Kirschner & Meester, 1988; Lazarowitz & Tamir, 1994; Lunetta, 1998). Despite this, we still hold on to lab as part of the curriculum because we believe regardless of the type of laboratory practices, it is worth it. The opportunity to visually observe chemical reactions, placing a piece of copper in a colorless solution of silver nitrate and watching the solution gradually turn blue, helps students connect to the chemical concepts (Hofstein, 2004) beyond the written word or the chemical equation. With this in mind, laboratory could still be the ideal place to allow students to engage in meaningful learning while fostering students' positive attitudes (Galloway et al., 2015; Lunetta et al., 2007).

Learning chemistry is challenging for many students. Its difficulty lies in the complex and abstract nature of the subject (Gabel, 1998; Johnstone, 2000; Tasker, 2014). While students can visually observe chemical phenomena at the macroscopic level (macroscopic view), the explanation of how and why things react as they do lies at the particulate level (particulate view), and usually all of this is summarized and expressed using symbolic representations (symbolic view). Visualization is a key to understanding chemistry concepts and has the potential to lighten the cognitive load for students. Let's take the situation of teaching oxidation–reduction. We define oxidation as the loss of electrons and reduction as the gain of electrons. We might introduce a macroscopic example like rusting to try to tie these definitions to the students' experiences. Then we jump to the symbolic treatment of oxidation and reduction by writing half reactions and following the loss and gain of electrons through the steps. Chemists are successful in chemistry because they see the connections between these three levels of representational visualization (macroscopic, particulate, and symbolic) and move seamlessly from one to the other (Johnstone, 2000; Taber, 2013; Talanquer, 2011;) and therefore do not overload their cognitive processes. Students, novices, treat these three levels of representation as discrete pieces of cognitive material that serve to increase the cognitive load associated with learning chemistry.

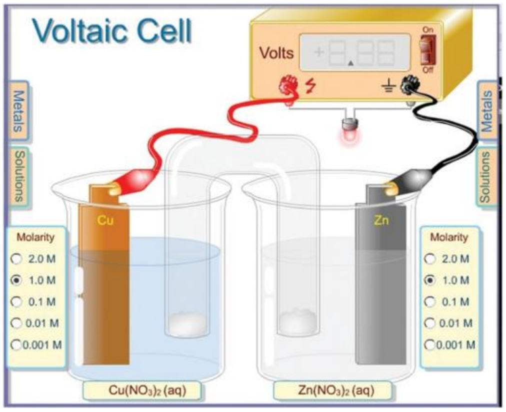
There is no doubt, chemists are very interested in the particulate representations of processes, and it is almost impossible to make a connection between the macroscopic level and the particulate level of understanding without some mental image of the way particles interact (Deratzou, 2006). Students do not see this connection and most do not develop it naturally. Since students are sense makers, they do build some type of explanation often creative and inaccurate. Misconceptions found in electrochemistry illustrate this point and are plentiful (Garnett & Treagust, 1992a; Ogude & Bradley, 1984; Sanger & Greenbowe (1997, 2000)). For example, since we cannot see electrons, some students form an image of electrons floating freely in a solution (Ogude & Bradley, 1984) without any assistance from the ions (Sanger & Greenbowe, 1997). Other students imagine electrons moving through a solution by jumping from one ion to the next (Garnett & Treagust, 1992a) or from one electrode to another (Schmidt et al., 2007). Often students see a circuit being completed within a galvanic cell by electrons flowing from one half-cell solution to the other through the salt bridge (Garnett & Treagust, 1992a). An inability to form an accurate image of what electrons are doing at the particulate level not only impedes students' abilities to acquire the correct conceptual understanding (Hamza & Wickman, 2008; Songer & Mintzes, 1994; Taber, 1995), but also prevents students from integrating the three level of representation during the process of learning (Ogude & Bradley, 1984; Sanger & Greenbowe, 1997). Therefore, if students could visualize an accurate particulate model it would enhance their understanding of the abstract concept (Doymus et al., 2010; Lee & Osman, 2012) and reduce the cognitive load associated with learning chemistry. In the last decade, many chemical educators have taken advantage of freeware programs, using them in both the lecture and in the laboratory to try to assist students in visualizing the particulate level. Computer simulations offer students an explicit view of the interactions at the particulate (sub-microscopic) level (Kozma et al., 2000; Kozma & Russell, 1997; Wu et al., 2001), and are often used as a pre-lab to prepare students for the chemistry laboratory (Krupnova, 2016; Winberg & Berg, 2007), as an alternative to the traditional laboratory for distance learning (Dalgarno et al., 2009; Krupnova, 2016) or as a wholesale replacement of the hands-on laboratory that is much more cost effective (Hawkins & Phelps, 2013; Tatli & Ayas, 2013). Viewing dynamic two or three-dimensional animations has been shown to help students learn to connect the particulate and the symbolic representations (Williamson & Abraham, 1995). Winberg and Berg (2007) found students who used the computer simulation visualization in the pre-lab asked more theoretical questions during the laboratory activity than the traditional group. When comparing achievement on a test following laboratory, students using a computer simulation lab and students in a traditional hands-on lab performed equally well (Hawkins & Phelps, 2013; Tatli & Ayas (2012, 2013)). While there are many studies that compare different laboratory techniques with computer simulations, rarely do these studies emphasize the type of visualization prominent in each type of laboratory and how it affects the dynamics of students' interactions in the laboratory. In an effort to gain a better understanding of these influences from the students' perspectives while engaging in an electrochemistry laboratory activity, we deployed two different types of laboratory techniques; a traditional hands-on lab where macroscopic visualization (MV) is prominent, and a computer simulation where particulate visualization (PV) is prominent. We listened to the students' discourse in hopes of gaining a better understanding of the impact each type of visualization had on students' learning experiences.

Methods

The student discourse data was initially collected from students who were taking the General Chemistry II (CHEM 1121) laboratory at a regional comprehensive university in the Southeastern United States in the Spring semester of 2011. We selected six out of 16 sections of the laboratory to participate in the computer simulation developed by Greenbowe (https://pages.uoregon. edu/tgreenbo/voltaicCellEMF.html) where the visualization was focused on the particulate level laid over an image of an electrochemical cell (Figure 2).

Figure 2

Electrochemical Cell



Note. Screen shot of simulation (used with permission of Dr. Thomas Greenbowe) https://pages.uoregon. edu/tgreenbo/voltaicCellEMF.html)

This selection was based on the availability of the space in the computer lab during the laboratory times. The remainder of the sections performed an electrochemistry experiment using the traditional hands-on approach where the visualization was focused on macroscopic visualizations (MV) such as observing a direct reaction, building galvanic cells, examining the impact of a salt bridge, and measuring voltages with a digital meter (White, 2005). In addition to being enrolled in CHEM 1121, students were enrolled in a General Chemistry II lecture in the semester in which they took this laboratory. Students choose the laboratory section based on a time that was most convenient for them with no regard for the lecture section they are enrolled in. Therefore, students in the simulation laboratories and students in the traditional hands-on laboratories could be in the same lecture sections. The quantitative data obtained from the pre- and post-test was analysed and the results were published in a previous issue of this journal (Hawkins & Phelps, 2013). Permission to use data from human subjects was obtained from our institutional review board (IRB) and informed consent was acquired directly from the students in the laboratory sections. We collected audio recordings from students who provided informed consent from each of the different laboratory techniques as they worked through the material. Six groups of students were recorded; three MV and three PV, four of which were transcribed in the summer of 2015. After we analysed the original data, we found the influence of each type of visualization on the dynamics of student interaction in the laboratory to be interesting, but due to problems we encountered with the quality of the audio-taping, we decided to recollect the student discourse data in the Fall of 2015 and in the Spring of 2016. A new IRB application was made and approved allowing us to continue this study. We selected 18 pairs of students; nine pairs of students from the laboratory sections that participated in the computer simulation particulate visualization activity and 9 others from the sections that participated in the traditional hands-on macroscopic visualization lab. In an effort to focus on the differences in visualization, others factors in the laboratory were made as similar as possible. We wrote similar procedures and questions implementing a Process Oriented Guided Inquiry Learning (POGIL) activity for both of the visualization approaches (www.pogil.org). The same professor taught the electrochemis- try lab for each section used in the study. The same researcher observed each laboratory section used in the study on the day of the electrochemistry lab. We audiotaped students' discourse, and videotaped them engaging in the entire electrochemistry activity with consent of the students being recorded. We used qualitative analysis software, ATLAS.ti, to aid with the coding of the data. The audio recordings were transcribed and a grounded theory framework was implemented. The use of grounded theory allowed us to approach the data looking for emergent categories or themes (Patton, 2015; Urquhart, 2013;). As the transcripts were read line by line, an open coding system was used to first look for patterns. The initial patterns in this data were ‘type of activity’, ‘who did the students talk to’ and ‘time spent in each activity’. The raw data within these patterns were further coded by two researchers independently and categorized looking for similarities and difference between the two different visualization groups in accordance with the constant comparison technique (Phelps, 1994).

Results

The first thing we noticed when comparing the discourse in these two environments was the difference in the total amount of time students spent in the laboratory. The traditional macroscopic visualization (MV) groups spent more time in the laboratory (127 minutes on average) than the simulation particulate visualization (PV) group (89 minutes on average) and the time that they did spend was not spent in the same way.

The data were sorted into categories reflecting the types of discourse that were identified in the transcriptions of the data. Figure 3. lays out the topics of discourse identified in the data and the percentage of time each group spent engaged in that type of discourse. The two types of discourse that we found most interesting when comparing the two groups were TA/student interaction and peer-to-peer discussion. MV students spent a greater percentage of their time in lab discussing things with the laboratory instructors, 26% (or an average of 33 minutes), compared to 13% (an average of 17 minutes) for the PV students. PV students spent a greater percentage of their time talking to each other, 66%, compared to 46% for their MV counterparts. Even though this is a greater percentage of time for the PV students it is approximately the same amount of time on average for both groups (just short of 59 minutes). Given the large amount of time both groups spent engaging in peer to peer discussion, this category was further broken down into sub-categories that are displayed in Figure 4.

Figure 3

Types of Discourse

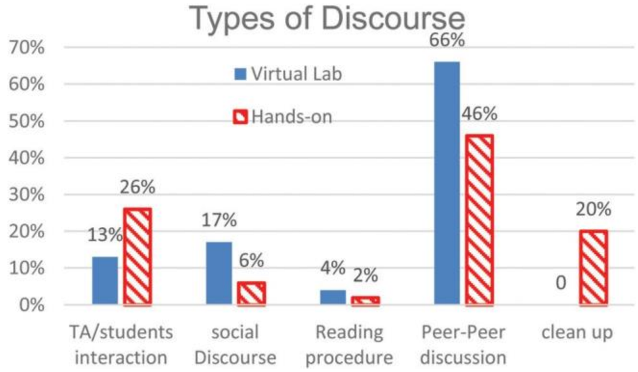
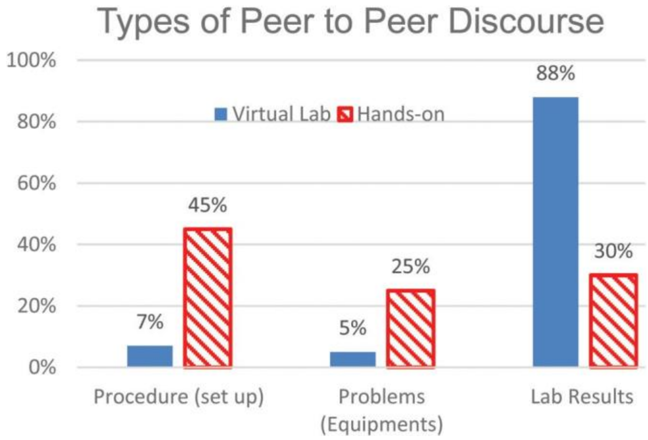


Figure 4

Types of Peer-to-Peer Discourse



Three types of peer-to-peer discourse were identified; procedures, where students were interpreting and setting up the experiment, problems, where students talked about issues with equipment or misunderstandings about how to use equipment, and lab results, which included discussing the data and what it might mean. While the number of minutes spent in peer-to-peer discussion were similar for the two groups, once you categorized the time into types of discourse, it was interesting that on average PV students spent 52 minutes discussing the results of the experiment compared to 18 minutes for the MV students.

The macroscopic visualization students spent the majority of their peer-to-peer discussion talking about setting up the experiment and carrying out the laboratory procedures.

> MV students:
>
> Jane: I read it and now I forgot.. . we need a digital multi- meter.
>
> Sally: Multimeter. We also need a Zn strip. Jane: Is that it?
>
> Sally: It should say on the beaker.
>
> Jane: Yeah, I know, but is that all I’m going to get over here?
>
> Sally: Let’s see here, in the second test tube, connect the zinc to one of the wire and place the Zn in the test tube... Yes, for now.
>
> Jane: What happened here? Sally: I don’t know.
>
> Jane: Oh, there we go.
>
> Sally: Does it hook them to here?
>
> Jane: What is this? Did it tell you where you set it (talking about the multimeter)?

Sally: It does not. MV students:

May: OK... lost it. OK... copper sulphate. Are you watching it?

Peter: Yeah

May: Ok ah.. .mmm...

Peter: Our test tube is small. Small test tube. May: Yeah

Peter: That's my mistake. May: Oh, it's a thing?

Peter. What did you say?

May: Three fourths. (filling test tube 3 full of solution) Peter: Three fourths?

May: Yeah. Ok. We're gonna drop the zinc in. Here we go.

Ok drop.

We did code 30% of the MV students' peer-to-peer time in the category of lab results, but most of that interaction focused on getting the data with little or no discussion about that data as illustrated by three discussions below.

MV students:

Nancy: It's the right one. Oh my god, it's cool. You get what you get...

Nancy: 1750... 1760 (calling out values on the multimeter) Drew: 1770.. . 1784

Nancy: Write it down, do it to it!

Steve: Three... it keeps going up... 300 and we going with 360

Peggy: 360 sound good, Write it down, do it. Monroe: point 11

Marilyn: point 11? Monroe: Yeah

Marilyn: Now number 2, or wait... number one without the salt bridge right?

Monroe: That was zero TA: Stable?

Monroe: Yes Marilyn: What is it? Monroe: 1.02

Marilyn: 1.02 ok... so number 3, and now switch the wires connecting the wire lead which had been originally connected to the zinc strip. So switch them again.

Monroe: Umhum... negative 1.02.

The discourse of the students in the macroscopic visualization group was filled with short quips focused on the collection of data both quantitative and qualitative and getting that data collected quickly. There was very little discussion about concepts in the hands-on (MV) lab when compared to the simulation (PV) lab. Not surprisingly, there was very little time spent setting up the experiment for the PV students given the nature of a computer simulation, but a higher percentage of the lab results discourse time was spent interpreting the results.

PV students:

Pepper: When I look at your reactions, and I say to myself which is the most reactive metal? It appears that the zinc metal reacts twice and the silver metal never reacted at all. But here it said the metal (sic) flows from the most reactive to the least reactive. You said silver was the most reactive.

Rey: Umm. The silver’s going around just reacting with everything?

Pepper: Good point. Probably not.

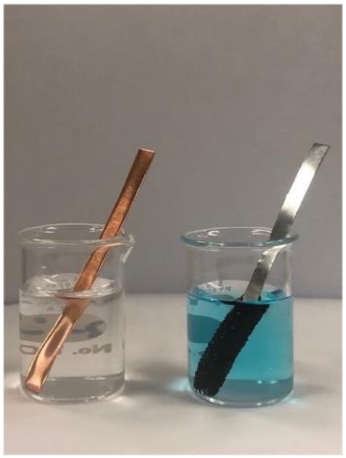
> Rey: So the difference is silver is plus one and the silver... comes out low metal reactivity when you think about the metal reacting... Looks like your example here. I have two cells for the zinc reactivity, one silver and one copper reactivity.
>
> Pepper: So the zinc, then copper and then silver. Yeah.
>
> Rey: Here, again.. . electrons getting over here trying to make silver.. .
>
> Pepper: OK. Zinc, copper, silver. So this is wrong then? And it should be the zinc reacts twice, copper reacts once, silver never reacts?
>
> Rey: How does the activity here of the metal compare to the position (on the table)? OK, now you look at the charge. So, zinc and then the copper and we are backwards. The higher activity is higher on the reaction (table), right?
>
> Pepper: Yeah? OK.

The simulation students spent more time talking about the results of the experiments and the concepts of electrochemistry. More time talking about concepts resulted in PV students revealing more misconceptions. In the previous conversation, for example, the students noticed that silver was the only +1 ion of the substances they were comparing and they wanted to use this as an explanation for the difference in reactivity. They pointed out that silver was the least reactive metal of the triad and the only one with a plus one charge. Although they noticed it, they couldn’t seem to build an explanation that works and eventually dropped the idea. The discussion between the MV students does not reveal as much conflict of ideas because they are focused on getting the numbers, but not explaining them.

It was striking to see how much more conversation about the concept of electrochemistry was happening when students observed the behaviour of electrons at the particulate level. Time was not the only difference in the conversations happen- ing between students in the two groups which becomes more evident when comparing students dealing with similar questions. Let’s consider the observation of a direct reaction where students were trying to determine whether copper metal in a zinc sulphate solution or zinc metal in copper II sulphate solution was spontaneous (Figure 5).

Figure 5

Hands-on Set Up for the Direct Reaction



Note. Direct reaction of copper metal in zinc sulphate solution (left) and zinc metal in copper (II) sulphate solution (right).

MV students:

Jane: So the metal definitely got darker from silver colour to orangey.

Sally: It got kind of rust coloured. Jane: It does...

Sally: So observations?

> Jane: You can see it looks fuzzy kind of. Sally: Changing in colour and texture
>
> Jane: Yeah, write that. You got looks orange and rusty I'm gonna take it out and see what it actually looks like. Sally: So the texture of the zinc is kind of like fuzzy?
>
> Jane: Yeah, you can see the fuzziness. Do you see it? Sally: Yeah, I see what you're talking about.
>
> Jane: Actually it's really cool!

The MV students made macroscopic observations that at times they clearly found exciting. Determining spontaneity for the MV people was about looking for a sign of a chemical reaction.

> MV students:
>
> Lillian: Would you say that it's clear? Adriana: Yeah, royal clear blue.
>
> Lillian: So... royal clear blue.
>
> Adriana: Drop it down... set my timer.. .
>
> Lillian: I did it... here we go. Adriana: Whoa.. . like.. . immediately.
>
> Lillian: At first I thought that.. . It kinda like turns black.
>
> Adriana: That's what I'm thinking.. . but I'm not sure what's black...
>
> Lillian: Throw stuff against the wall.. . maybe it's displacement?
>
> Adriana: At first... Would you say the solid turned into black or into the zinc?
>
> Lillian: lt kinda looks like...
>
> Adriana: Interesting...

Lillian: Yeah, I think.. . it (the reaction) is happening... and then...

Adriana: I guess you could say after one minute the zinc is deteriorating.

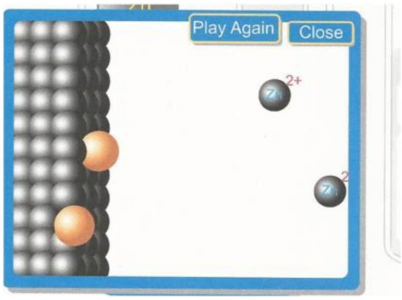
Lillian: And the copper?

The students reported their observations but did not explore why one reaction occurred and the other did not.

The PV students were also encouraged to set up a direct reaction by placing the copper electrode in the simulation in a solution of zinc nitrate and a zinc electrode in a copper II nitrate solution. The direct reaction was animated for the students at the particulate level (Figure 6).

Figure 6

Particulate View of the Direct Reaction



Note. Screen shot of animation of a direct reaction (use with permission of Dr. Thomas Greenbowe) https://pages.uoregon. edu/tgreenbo/voltaicCellEMF.html)

It would be reasonable to assume that the PV students who could actually see the electrons moving and the ions becoming atoms again would have an easier time determining which reaction was spontaneous.

PV students:

Rija: Nothing happens except for this (pointing at the simulation).

Jalon: All the copper went in and zinc out there Rija: Copper goes in and reacted to zinc

Jalon: So copper attached to the zinc and zinc 2+ releases Rija: So copper ions go into zinc by taking in the zinc's

electrons and they become solid.

Jalon: So that means the.. .

Rija: It's spontaneous.

Jalon: Yeah.

Rija: Zinc put in copper nitrate so we know zinc started off with zero and then they become a plus two. Copper started out as a plus 2 become zero, so the zinc being oxidized because it's giving up electrons. Which means the copper's being reduced. And the nitrate is just a spectator and there's no reading (on the meter). At this side where copper ions and zinc solid meets that's where reaction is taking place. There's no reading on this.

Jalon: Yeah.

The PV students were trying to answer the same question as the MV students about which reaction was spontaneous, but they talked more about the process than their MV counterparts. While it seems that seeing the electrons moving was helpful to the group above, it wasn't helpful to everyone.

PV students:

Karen: .. . I like this visual lab, don't you? Richard: Yeah, we don't have to pour anything out Karen: Especially the buffer solutions (?)

Richard: Which species loses electrons? That would be copper because it is 2+.

Karen: Ok Richard: Right.

Karen: And zinc is gained Richard: Yeah

Karen: The loss of electrons is oxidation. The gain of electrons is reduction.

Richard: This is the half one. Do we need to write that? Karen: I don't think so

Richard: OK. So the loss of electrons is oxidation, so the gain is reduction. The zinc is acquiring electrons.

Karen: We are not writing here or just circle? Richard: Just circle

Karen: The oxidation agent is the zinc and select one.. . Okay.

These students saw the particulate level animation and they were able to recite the definition of oxidation and reduction, but this did not lead them to the correct interpretation of the reaction. The question of spontaneity continued as the students moved from observing direct reactions to working with galvanic cells (Figure 7).

MV students:

Sam: These transfers are useful... Is there cell potential (on the meter)?

John: Wow! Do we have electricity!!?

Sam: This is really sick (?). If we have to we can just keep messing with this for the whole lab.

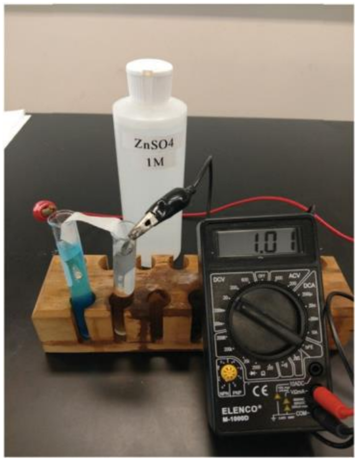
John: Yeah, we do! (answering his own question)

The MV students were still interested in getting readings from the meter and were excited to see that they had created ‘‘electricity’’. They did not express concerns about determining spontaneity although they were, at times, confused about the sign of the voltage on the meter.

> MV students:
>
> Marilyn: What is this? Did it tell you where to set it? Monroe: It does not.
>
> Marilyn: Get two copper and two zinc.
>
> TA: One copper and one zinc. Did they tell you where to place the copper?
>
> Monroe: Connect a strip of zinc to a wire lead and place the zinc strips in the test tube containing zinc sulphate (Figure 7).
>
> Monroe: Ok here comes the salt bridge Marilyn: That went in nice and easy Monroe: Ok
>
> Marilyn: It’s negative, but if we switch it, it will be the same number but positive. So I just have an absolute value of it.
>
> Monroe: Ok, so we take an absolute value of the voltage? Marilyn: Yeah, if it stops moving... It’s gone from 0.08 to
>
> 0.3. This is Cu and Fe? Monroe: Umhum.
>
> Marilyn: Ok... 0.33. Is it capital V or measured in ohms?
>
> What’s the literature say?
>
> Monroe: I don’t really know.

Figure 7

Galvanic Cell from MV Lab



Most MV groups did not spend much time explaining their results. The peer-to-peer discourse was much more utilitarian for the MV students. When there were samples of student thinking demonstrated within these MV groups, it was usually initiated by the laboratory instructor (either a graduate teaching assistant or a professor).

> MV students:
>
> TA: So which one of these three metals are the most active? Marilyn; The copper and magnesium.
>
> TA: So you have to name only one. Marilyn and Monroe: The magnesium.
>
> TA: And the least reactive will be.. .? Marilyn and Monroe: The iron.
>
> TA: What’s your reason?
>
> Marilyn: Mg is further on the left side of the periodic table so it more easily gives up electrons than iron would.

> TA: Can you explain from the data that you obtained from the experiment?
>
> Marilyn: So the Mg easily allows the electrons to be trans- ferred to the copper.
>
> TA: OK but how do you know that?
>
> Monroe: When copper and iron were used, a lot of voltage generated. Anytime Mg was used, the voltage generated was more so.. .
>
> TA: Very good. In here, you see when Mg and copper...
>
> 1.86, right?
>
> Monroe: Yes ma'am
>
> TA: And here you have Mg and Iron at 1.44.
>
> Marilyn: And then just copper and iron then it's only 0.33. And so we can see that there's not a big difference of electrons causing the electrical current.
>
> TA: Why do you say that Mg is the most active?
>
> Marilyn: Because it generates the greatest voltage than any other combination. Anytime magnesium is in there the voltage is much greater.
>
> Monroe: Yes
>
> TA: And you said iron is the least?
>
> Monroe: Yes. It is the same concept. Many times when iron is in there it's less active.

The TA tried to encourage the students to explain their choices for the answers to the questions regarding the reactivity of metals using the data generated by building the various galvanic cells. You can see that the students have the beginning of a concept of activity of metals as it relates to galvanic cells although there are still holes. The idea that a cell containing magnesium will always have the higher voltage works for these three metals but is not applicable to all cells containing magnesium and they never tied the trend back to relative reduction potentials. Similar conversations happened between the PV students without the prompting by the TA (see Pepper and Rey earlier).

The PV students had a similar galvanic cell set up which included a digital meter much like the one used in the hands-on laboratory (Fig. 5). The PV students were able to observe electrons moving through the cell which gave them an advantage when answering questions about a galvanic cell.

> PV students:
>
> Mick: Here (in the simulation), you can actually see—you can actually see what’s going on.
>
> Mariam: You can also see the copper is sticking to the metal.
>
> Mick: Electrons moving through the wire and then attracting the copper, yes.
>
> Hattie: Yeah, I agree. Plus, oh.. . first two electrons. Mark the cathode. The anode, I am pretty sure is zinc and the cathode is this (pointing), because that’s what she said, yesterday, right?
>
> Daniella: Yes, it (the electron flow) goes from anode to cathode and then from zinc to copper. Cathode is copper?
>
> Hattie: Yes.
>
> Daniella: Anode is zinc.

> Hattie: Perfect, so is this still a spontaneous reaction?
>
> Daniella: No, is that where we add at the values and we would do zinc backwards, so it will be positive 0.762. And copper would be the positive, so it's not... it's not spontaneous.

These PV students could see the electrons moving from the anode to the cathode in the animation. They could see how these electrons eventually combined with the cations in the solution of the cathode half-cell (Fig. 7). Despite this information they still had trouble deciding if what they were seeing was a spontaneous reaction even after calculating a positive cell potential. They seemed to confuse the sign convention for cell potential for a product favored reaction with the sign convention for the change in free energy of a spontaneous reaction.

The calculation of the cell potential was a source of confusion for many students. The calculation of the cell potential is presented in two different ways within our department and in the textbooks in use in our general chemistry courses. One approach is the calculating of the cell potential as the difference in the reduction potential of the cathode and the reduction potential of the anode. The other approach instructs the students to take the sum of the reduction potential of the thing that is reduced (cathode half reaction) and the oxidation potential of the thing that is oxidized (the opposite sign of the reduction potential). The electrochemistry laboratory fell at the beginning of the study of electrochemistry so most students had been introduced to the definitions of oxidation and reduction, but had not engaged in a lot of practice with writing half reactions.

> PV students:
>
> Lauren: Which one is the table of...

Anthony: Probably refers to like looking up in here and see which one... Confirming one is bigger than the other one. I'm going to ask her.

Lauren: Ok, zinc

Rezhin: Zinc is point seven six.

Anthony: So, you do need a table as a reference. Rezhin: Ok, thank you.

Lauren: So zinc has a voltage of negative seven six and silver positive point eight zero. So the difference is 0.04 or point seven six minus point eight zero.

Rezhin: I think zinc is negative point seven six plus point eight zero cause in class today we.. .

Lauren: We did ah...

Rezhin: But still, I don't know if it pluses or minuses in general.

Lauren: yeah

Rezhin: I don't know. I guess we just add them.

Lauren: Point eight minus point three four gives you a point four six (reading the value off the simulation) so that point zero four?

Lauren: So I notice if it's a really small number then...

Rezhin: Yeah so it's smaller than the lowest voltage because I added in point three four (0.34) and point eight oh (.80) and the one point.

Lauren: Or.. . Ok if that.. . then we have to compare which one made the smallest (reading on the voltmeter), copper and silver. So copper is point three four (0.34) and silver point eight zero (0.80). Add those together, one

> point one four (1.14). So I guess the higher the.. . I don’t know if it’s correct. The higher the voltage, the.. .?
>
> Rezhin: The higher the voltage, the lower the.. .? Lauren: The current?
>
> Rezhin: the reduction potential?
>
> Lauren: I think zinc is the most reactive and then copper and then silver.
>
> Rezhin: Yeah
>
> Lauren: Cause zinc is the oxidizer for both copper and silver. Copper is the oxidizer for silver and silver is never the oxidizer.
>
> Rezhin: That makes sense.
>
> Lauren: So how does the activity of the metals compare to their position on the table?
>
> Lauren: Zinc is up here, negative point seven six (-0.76) and both copper and silver are positive. Copper being point three four (0.34); silver point eight (0.8). So the higher the number the less reactive. The anode’ll be the zinc.

These students could see what was happening at the particulate level, but had trouble connecting that to the symbolic representation required to calculate cell potentials from a table of standard reduction potentials. They even seemed confused as to how the values on the standard reduction potentials table were related to the value on the voltmeter in the experiment. They made attempts to apply vocabulary, but confused the idea of things that are oxidized and things that cause other things to be oxidized (reducing agents). It is interesting that while the vocabulary was not accurately applied, the students were able order the metals in terms of reactivity correctly and identify that zinc would be the anode of this triad of elements. The PV students persisted in this type of discussion without intervention from the laboratory instructor.

Students in both the macroscopic visualization lab and the particulate visualization lab were asked to identify which electrode loses mass in the galvanic cell. The macroscopic visualization students responded in a very macroscopic way, simply reporting what they saw.

> MV students:
>
> Andrew: It looks like this one is thinner.
>
> Nicholas: Yeah, It looks like it's thinner and maybe lighter? Andrew: So zinc is getting smaller—will it go away complete? Nicholas: We only have to say which is smaller.

Initially, the PV students also responded based on what they saw; an electrode getting smaller as electrons travel up the wire and ions leave the anode and enter the solution. The PV students saw which electrode lost mass in the animation, but they tried to explain why this was true.

> PV students:
>
> Mick: So the one that loses electrons should be the smaller one.
>
> Ringo: I guess that makes sense losing stuff should make it smaller.
>
> Mick: Ok so losing is smaller. Ringo: Yeah seems too easy. But.. .
>
> Mick: Well losing electrons means you have more positive charges than negative so that makes it smaller. That makes sense, right?
>
> Ringo: Sure I guess—so the smaller one is zinc?
>
> Mick: Yeah zinc is smaller and copper is bigger since it gains electrons.

> Mick: (laughing) Ok time to get serious, I’m sorry. Ok any- way the one that gets smaller is the one that loses electrons. The one getting bigger is the one that gains electrons.
>
> Ringo: Ooh yeah.
>
> Mick: Because electrons’ repulsion tells us that atoms or ions will get bigger.
>
> Lauren: Each cell in the simulation reacts, which half-cell shows the metals getting smaller?
>
> Raleigh: The smaller?
>
> Lauren: The smaller one would be solid, wouldn’t it? So it would be... because it’s the ion that is positive means there’s not many electrons out there so it holds it tight together.
>
> Lucy: Which half-cell shows the metal getting smaller?
>
> Ricky: It would be the one that gives away the electrons that will get smaller because it gives away zinc ions.. . right?
>
> Ricardo: Right? This one’s gaining silver ions into it. Ricky: So cell A, copper is getting smaller.
>
> Ricky: The one that gives off the electrons is smaller because the nuclear pulls from the nucleus.

Despite their good scores on the laboratory assignment, the students revealed some misconceptions as we listened to them that were not evident when merely grading their papers. For example, these students in the particulate visualization group correctly identified the electrode losing mass, but provided well thought out and incorrect particulate level explanations for why they made the choice they made. At times they seemed to equate ‘‘pieces of metal’’ and ‘‘metal ions’ since they are both classified as metals on the periodic table. They also used relationships that explained why cations are smaller than their respective neutral atoms to pick the electrode that is ‘‘getting smaller’’ as the electrochemical cell proceeds. The students’ reasoned that losing something should make you smaller but they incorrectly explained this by applying the idea that a loss of electrons causes an increase in the effective nuclear charge which makes the ion radius smaller than the neutral atom radius. Most of the students seemed to ignore that the ions produced by the loss of electrons would be water soluble which would reduce the mass of the anode. This happens despite the fact that the simulation shows cations leaving the anode in one half cell and other cations sticking to the cathode in the other half cell. The students in the macroscopic visualization group also had no trouble choosing correctly the electrode that loses mass. These students just reported the one that looked smaller as smaller without thinking about why that might be true.

Discussion

Assertion: the type of visualization heavily influences the discourse in the laboratory. The type of visualization offered in the laboratory students engaged in impacted who they talked to and what they talked about during the electrochemistry laboratory activity. For students in the traditional hands-on laboratory, the macroscopic view is the critical aspect of the object of their learning and they pay very little attention to the particulate view. They seem to be satisfied with short answers that emphasize colour, texture and meter readings as the important features for completion of the lab. While MV gave students first hand experiences with chemical reactions that, based on their verbal expressions of excitement from the audio tapes of ‘‘cool’’, and ‘‘wow’, engaged them in the activity, the students don’t readily demonstrate that this mode of visualization is leading them to a deeper understanding of electrochemistry concepts. Instead, their dis- course focuses on reading and interpreting procedures, and setting up equipment, leaving only 12% of their time in laboratory engaged in peer-to-peer discussion of the laboratory results. The interactions MV students did have with their peers were generally short, with little or no negotiation of ideas between lab partners and no evidence of making connections to the particulate level of representation. These results, however, do not mean macroscopic visualization has no place in developing conceptual understanding of electrochemistry. The MV students talked more to the instructor in lab and these interactions often led to the development of concepts. The discourse between the TA and students showed that, with careful questioning and guiding from the TA, the students were able to evaluate their data and apply their findings to new situations and were able to order the reactivity of metals correctly. We want students to be excited about chemistry and develop a macroscopic practical understanding of concepts. For example, the macroscopic visualization was powerful for driving home macroscopic questions, such as which electrode loses mass in a galvanic cell.

The particulate visualization (PV) students talked to each other more than the MV students did and more of that discussion involves interpreting the results of the data collected. Unlike MV groups, where physical phenomena seemed to be the highlight of the experiment, the PV groups, while fascinated with the display of chemical reactions at the particulate level, seemed to focus more on the concepts and interpreting what was happening at the particulate level. While these groups of students provide rich information on how particulate visualization influences how students construct their understanding of electrochemistry, they also reveal various misconceptions. When given these particulate level visualizations, students are cued to try to provide particulate explanations for even macroscopic questions like which electrode gets smaller. PV students consistently carried on involved conversations trying to work out the details to explain phenomena they were observing without prompting from the laboratory instructor. Perhaps due to their relatively low engagement with the laboratory instructors, PV students were not always challenged when they developed alternative explanations that led them to correct answers. This would indicate that the particulate visualization alone is somewhat lacking in helping students develop a complete understanding of chemical processes.

The data in this study demonstrates the strength of the visual phenomenon that students are engaged in when it comes to the type of thinking on display. The activity the students were engaged in heavily influenced the things students talked about. This is important for us to know—it is important for those of us designing laboratories to decide what we want students to get from the laboratory experience and to design accordingly. If we believe that the multiple representations as explained by Johnstone (1983) are important for the learning of chemistry then we need to think about how to use the laboratory to help students make these connections. The laboratory should be a place of excitement where students get a macroscopic sense of chemistry and a WOW factor which was the case for the MV students, but chemistry is also about the particulate understanding since the explanations for most of what students observe at the macroscopic level lie in the particulate level. While both the MV and PV students responded in ways con- sistent with the primary visualization used in the laboratory they were engaged in, PV students were more likely to explore the ‘‘whys’’ associated with their observations. Both of these results are desirable; excitement about seeing chemistry happen and talking about why chemistry happens that way.

If we want lab to be meaningful (and worth the money and time spent), we have to be more explicit with our objectives and more precise in our design. These data indicate that the type of visualizations we provide the students influences what they think about even when answering the same types of questions. At many institutions the laboratory has remained fairly unchanged for decades, focusing on techniques of data collection and macroscopic observations of chemical phenomena. These types of activities seem to pique the interest of some students and provide a sense of excitement about chemistry. This macroscopic experience is important to the understanding of chemistry, but so is the development of a particulate view of matter. Which begs the question, what would be the impact of combining the two methods? It seems reasonable that combining both the MV and PV approaches into one laboratory experience might help students connect all three levels of understanding; macroscopic, particulate and symbolic. This is in fact what we are doing now and we are excited about this on-going study. There is a large block of time carved out for this laboratory experience and we continue to seek ways to keep the macroscopic benefits while capitalizing on the unused time to enhance particulate understanding as well.

Conflicts of Interest. There are no conflicts to declare.

Acknowledgements

The authors would like to acknowledge the help of Dr Gary White who allowed us to work with the students in the CHEM 1120 labs. We would also like to thank Drs Keying Ding and Preston MacDougal for allowing us access to their students. We are also grateful to the students involved in the study who were willing to let us listen in on their conversations.

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CHAPTER 4: MAKING CONNECTIONS: A QUALITATIVE STUDY OF ELECTROCHEMISTRY IN THE LABORATORY

Abstract

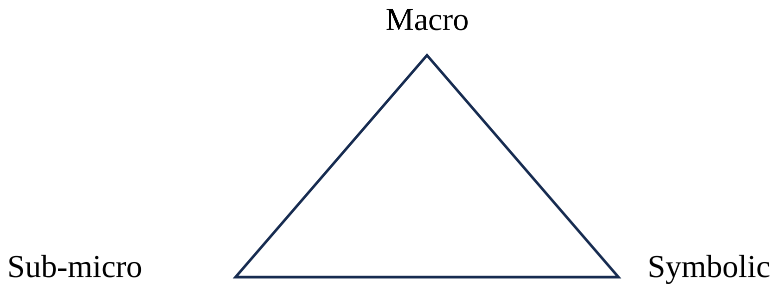
Chemistry is considered a difficult subject by most students. Its difficulty lies in chemistry's complex and abstract nature. Chemistry can be expressed as a function of the macroscopic, particulate, and symbolic. Experts can successfully navigate the various representations without overloading their working memory because they can relate their macroscopic observations to the particulate compositions, structures, and properties, and express these symbolically. This ability to seamlessly connect the three levels of representations is not intuitive to novices/students. Working with all three representations can lead to cognitive overload as the novice thinks about all three representations independently. In a previous study, we investigated the effects of different visualizations on students’ discourse while performing a laboratory experiment delivered in a hands-on (macroscopic) versus a computer simulation (particulate) format. In this study, we investigate the type of discourse students engaged in when the laboratory activity included both macroscopic (hands-on) and particulate (simulation) styles in the laboratory. We found not only that the type of laboratory setting influences the type of discourse (i.e., macroscopic or particulate talk) but that students receiving both hands-on and simulation experiences developed better connections among the three levels of representations and used different representations more often as part of their discussions than students receiving just the hands-on or the simulation experiences.

Introduction

The modern view of learning chemistry involves the interplay among three distinct but related representations—the visible (i.e., macroscopic), the invisible (particulate), and symbols, models, and formula (i.e., symbolic) (Chandrasegaran et al., 2007; Johnstone (1991, 1993, 1997); Lin et al., 2016; Ramnarain & Joseph, 2012; Treagust et al., 2000; Tsaparlis, 2009). In modern-day chemistry, the three domains of representations have played a central role in reasoning, communicating, thinking, and facilitating learning within the chemistry community (Chandrasegaran et al., 2007; Johnstone (1991, 1993, 1998); Lin et al., 2016; Ramnarain & Joseph, 2012; Treagust et al., 2000; Tsaparlis, 2009). It is a key to understanding chemistry (Reid, 2021). The nature of modern chemistry is highly abstract and requires constant interplay and coordination between the macroscopic, particulate (sub-microscopic), and symbolic representations. Johnstone original explanation about the three domains of representations is useful here. It appears as a triangle with three vertices: descriptive and functional = Macro (i.e., a tangible and observable), representational = Symbolic (i.e., shorthand notations representing formula and chemical reactions); and explanatory = Sub-micro (i.e., explanation to the observation) (Johnstone, 1982; Talanquer, 2011). He created a model that shows their interconnectedness (Figure 8), and it has been used as a framework by chemical educators to show the relationship between these three representations. His original model was labeled as macro, sub-micro (i.e., particulate), and symbolics or from conceptualist chemistry situations: macroscopic (a sensory way), particulate (a qualitative way), and symbolic (both qualitative and quantitative way) (Reid, 2021).

Figure 8

Johnstone’s Triangle of Representation



Note: Macroscopic (a sensory way), Sub-micro (a qualitative way), and Symbolic (both qualitative and quantitative way) (Reid, 2021).

Macroscopic Representation

Many of the great discoveries in chemistry started because of curiosity about the macroscopic nature of phenomena. Lavoisier, the Father of Modern Chemistry, combined the power of macroscopic observation with careful measurement and systematic series of experiments, changing chemistry from a qualitative to a quantitative science (Carcolice & Peter, 2020). Chemists (and novices) experience macroscopic levels through their senses (i.e., seeing, hearing, touching, smelling, and tasting) (Johnstone, 1991, 1993, 2000). Novices are familiar with this mode of operation, so Johnstone recommended that this would be the best starting point for the three representations (Johnstone, 2007). Johnstone recommended that novices stay at the macroscopic level until their knowledge is anchored before moving on to the others (Johnstone, 2009). Learning in the hands-on laboratory is an example of how students experience the macroscopic representation in scientific settings by measuring, observing, and categorizing chemical phenomena

(Gabel, 1999; Hinton & Nakhleh, 1999; Treagust et al., 2003; Tsaparlis, 2009). A hands-on laboratory is a learning approach designed to give students a macroscopic experience. Students show excitement when seeing the macroscopic changes, such as light flashes, color changes, bubble formation, and precipitations appearing (Hunter et al., 2019). The hands-on also promotes macroscopic discourses (Hunter et al., 2019).

Particulate Representation

Johnstone originally labeled this domain of representation as ‘sub-micro.’ This level of representation is also known as, ‘atomic level,’ ‘molecular level,’ ‘microscopic,’ and ‘sub-microscopic’ are all in use and are used interchangeably with the word ‘particulate,’ which includes atoms, molecules, electrons, and inter- and intra-molecular forces (Chandrasegaran et al., 2007; Treagust et al., 2003). The particulate nature of matter is invisible to students’ normal senses or experiences, making it the most difficult concept for students to understand (Gabel et al., 1987). However, the particulate representation explains why matter looks or behaves like it does (Van Berkel et al., 2009). For example, why does a raindrop have a teardrop shape, flattened on the bottom with a curved dome top (macroscopic level)? The answer to this question requires an understanding of the molecular geometry of water, the inter- and intra-molecular forces, the adhesive and cohesive interaction, and the chemical composition of water (particulate level) (Van Berkel et al., 2009). Because students cannot see matter at the particulate level, it is difficult for them to form an accurate mental model to explain chemical phenomena (Chittleborough et al., 2002), leading students to form misconceptions of chemistry concepts (Ozkaya, 2002; Ozkaya et al., 2003; Tsaparlis, 2019). Computer simulations and animation technology has been used for over the decade to enhance conceptual understanding (Davidowitz & Chittleborough, 2009) by displaying a detailed view of the atoms and molecules and their interactions at the particulate level (Wu et al., 2001), making these abstract concepts fundamental and observable (Suits & Sanger, 2013; Yang et al., 2003), and promoting particulate discourses among students (Hunter et al., 2019).

Symbolic Representation

Symbolic representation is considered one of the oldest forms of language used to represent matter and has undergone several transformations (Fabbrizzi, 2008). Egyptians used Platonic solids (Joly, 2014; Restrepo & Villaveces, 2012), and alchemists used pictorial symbols and the names of Greek gods (Fabbrizzi, 2008; Martin, 2001; Morris, 2015), but it was Berzelius who first used letter symbols for the elements (Barke et al., 2009; Fabbrini, 2008). Nowadays, the symbolic representation is more than just atom types; it expands to include units of measurement, various measurable quantities, algorithmic relationships, molecular models, graphs, chemical equations, structures, and chemical processes (Chandrasegaran et al., 2007; Johnstone (1993, 1997; 2000); Ramnarain & Joseph, 2012; Taber, 2009). Experts have years of learning and know the meanings of the various symbols used as symbolic representations. On the other hand, Novices often treat the symbolic representation like a second language (Taber, 2009), with little or no pre-existing knowledge to help interpret their meaning and, therefore, are easily overloaded by their cognitive demand. Both the symbolic and particulate representations use symbols to stand for abstract entities. Treagust et al. (2003) compared the understanding at these two levels of representation as knowing how (symbolic) and knowing why (particulate). It is difficult to explain the particulate nature of chemical phenomena without some form of model (symbolic). For example, it is difficult to talk about the behavior of benzene molecules (particulate representation) without drawing some molecular model, like C_6H_6 or a six-membered ring with alternating single and double bonds (symbolic representation) (Taber, 2009). While chemical models (symbolic) make particulate representations visible and concrete (macroscopic) (Taber, 2009), it still requires a relevant domain of knowledge (Taber, 2009) to interpret the model (Chittleborough et al., 2002). Gabel et al. (1987) asked high school students to explain the meaning of '3 $H_2(g)$' in a chemical equation. Half of the students said it meant three molecules of H_2; the other half said it said six hydrogen atoms.

The traditional teaching method emphasizes an algorithmic approach to solving chemistry problems (Berkel et al., 2009) without explicitly connecting to the underlying concepts (Nakhleh & Mitchell, 1993; Tsaparlis, 2021). As a result, students memorize chemical formulas without conceptual understanding and often plug numbers into the wrong formula (Berkel et al., 2009) or invent a non-mathematical strategy of their own (Schmidt, 1994) to solve chemistry problems. The evidence of the disconnect between the algorithmic approach and conceptual understanding can be found in several studies involving electrochemistry (Sanger & Greenbowe, 1997a, 1997b, 2000), gas laws (Nurrenberg & Pickering, 1987), stoichiometry problems (Gabel, 1993; Sawrey, 1990); and acid-base reactions (Bodner, 1992). In all cases, students can solve problems using an algorithmic approach but not when presented with a similar problem using different representations (e.g., graphs, particulate views, particulate explanations). Many misconceptions in electrochemistry result from this disconnect which is not addressed in the traditional method of teaching (Lin et al., 2002; Ogude & Bradley, 1994; Sanger & Greenbowe (1997a, 1997b, 2000); Schmidt et al., 2007).

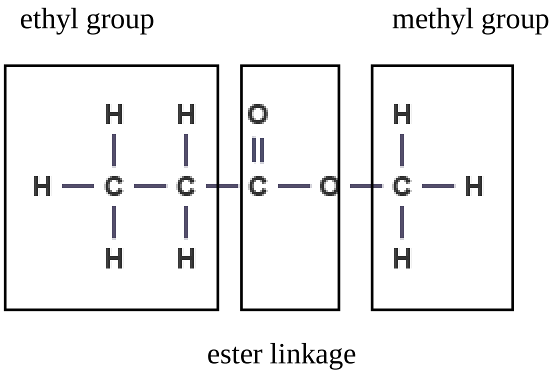
Working Memory and Students' Learning Difficulties

Macroscopic, particulate, and symbolic representations are integral parts of modern chemistry. However, using all three representations simultaneously to explain chemistry concepts can overload students' working memory if they see them as discrete pieces of information.

In the mid-late 1960s, Johnstone wondered why students found chemistry difficult (Johnstone et al., 1977). He and his students investigated which of the chemistry concepts students had difficulty with. They found that students need help in the area where the problem solver requires several steps to solve a problem. In the late 1970s, Natalie Kellet, Johnstone's student, collected data from students solving condensation and related organic reactions. She observed that students started having more difficulty solving organic problems as the number of steps involved in solving problems increased. After consulting with her professor, Johnstone, they hypothesized that problem-solving depends on students' ability to effectively chunk the information (Johnstone & Kellett, 1980). They explained that the expert reduced the working memory load by chunking information into a familiar pattern. The expert reduces the structure of methyl propanoate into three chunks; an ethyl group and a methyl group which join together by ester linkage (Figure 9). On the other hand, the novice saw 14 unrelated letters joined by single or double bonds. They simply overloaded their working memory and could not reproduce the structure (Johnstone & Kellett, 1980).

Figure 9

Methyl Propanoate



Johnstone explained that the limitation of working memory appears to be responsible for many students' learning difficulties in chemistry. (Johnstone & Kellett, 1980; Johnstone, 2009; Reid, 2021; Sirhan, 2007; Tasparlis, 2009). Working memory (WM) is part of the brain that temporarily holds and processes information received from the external senses. It is limited space, and an average person can only maintain and process seven chunks of information simultaneously at any given time (Miller, 1956). Since it is a shared space between temporary storage and the processing of information, the more information it holds, the less information can be processed. Short-term memory is overloaded above this magic number of seven, and students' processing performance is sharply reduced (Miller, 1956; Reid, 2021). Experts reduce the demand on working memory by chunking information into groups (Baddeley, 1997). Chemists do this by combining all three representations of knowledge in one chunk, increasing efficiency and lightening the load on working memory. Novices with limited prior knowledge of chemistry concepts cannot perform this “chunking” and instead process each piece of new information as its own chunk, which can easily overload their working memory.

Students can identify with what they have already experienced and what makes sense to them, and learning will be meaningful if the new knowledge is built upon what students already know (Bodner, 1986; Johnstone, 1997; Lamba, 2008). Johnstone’s suggestion aligns with Ausubel’s meaningful learning theory (Johnstone, 1997). For the learning to be meaningful, students must have prior knowledge that the new information can be related to, and the new information can be either assimilated into existing knowledge or existing knowledge is accommodated to form new understanding (Bretz, 2001). In other words, what students learn is controlled by what information they deem important and what has already been stored in their long-term memory (LTM). Unlike WM, where space is limited, LTM has unlimited storage space and can maintain information for an extended period (Baddeley, 1997; Stieff & Ryan, 2008). LTM informs a filter for what students pay attention to, which new information is selected (Johnstone, 1997; Lamba, 2008), and how that information is interpreted (Tsaparlis, 2009). The new information can be assimilated (i.e., interpreted, rearranged, and compared) to fit the prior knowledge or accommodated (i.e., modified, re-interpreted, and subsumed under more inclusive concepts) in the working memory, and this newfound knowledge can be stored back in the LTM to be retrieved and access in the future (Johnstone (1997, 2000); Lamba, 2008; Reid, 2021). Any learning without attachments to the LTM is not meaningful and becomes rote learning (Johnstone (1997, 2010); Reid, 2021) that can be easily forgotten. To avoid overloading students’ working memory, Reid (2021) concluded that chemistry curricula should make sense to students. The new concepts should relate to students' prior knowledge and be introduced in small steps.

Purpose

Our research group was interested in determining whether learning in the laboratory setting helps students connect ideas across the three representations. In a previous study (Hunter et al., 2019), we examined the impact of students performing a hands-on laboratory (MV-using macroscopic visualization strategies) versus students performing the same experiment using a computer simulation (PV – particulate visualization strategies) on students' learning and how learning varies in each type of laboratory setting. We found that the type of laboratory style influenced the type of discourse the students typically used in the laboratory. Each laboratory style had its strengths and weaknesses in helping students learn the chemistry content. The findings also led us to the question of what students' discourse would be like if they performed both laboratory styles (i.e., macroscopic and particulate visualization) in the same laboratory session. We named this type of laboratory MPV. Would students build connections between the macroscopic and the particulate if they performed the same laboratory procedure using both visualization styles, and would their explanations extend to include symbolic representation? Furthermore, could it be done within three hours of lab time? Ultimately, the answers to these questions will help us design and implement better laboratory activities, improve students' learning in chemistry, and perhaps provide support for keeping the laboratory as part of the chemistry learning experience at the freshman level.

Methods

The student discourse data was collected from students taking the General Chemistry II (CHEM 1121L) laboratory at a regional comprehensive university in the Southeastern United States. In addition to being enrolled in CHEM 1121L, students were enrolled in a General Chemistry II lecture in the semester in which they took this laboratory. Students choose the laboratory section based on a time that is most convenient for them, with no regard for the lecture section they are enrolled in. In the Fall of 2015, during the week that we performed the electrochemistry experiment, we selected six pairs of students from two laboratory sections: three groups of students from one of the laboratory sections that participated in the computer simulation developed by Thomas Greenbowe and accessed through his website at the time of this study (https://pages.uoregon.edu/tgreenbo/voltaicCellEMF.html), and three groups of students from the other sections that participated in the traditional hands-on laboratory. Based on the results we collected in the Fall of 2015 which were published in the Chemical Education Research and Practice (Hunter, 2019), led us to question the impact of combining the two methods on students' learning and whether the combination of the MV and PV approaches into one laboratory experience helps students connect all three levels of understanding: macroscopic, particulate, and symbolic. The new data was collected in the Spring of 2016. The new institutional review board (IRB) was obtained, and informed consent was acquired directly from the students in the study. With the students' consent, we collected data from five groups of students who participated in the MPV activities. We audiotaped students' discourse, videotaped them engaging in the entire electrochemistry activity, and copied their laboratory worksheets. The same professor taught both the lecture and the lab. Students in the MPV groups performed both laboratory styles (i.e., hands-on and computer simulations) in the same laboratory session. The laboratory activity was written as a Process Oriented Guided Inquiry Learning (POGIL) activity (www.pogil.org), which follows three stages: exploration, concept invention, and application. In the exploration stage, students explored the electrochemistry concepts through the redox equations (i.e., symbolic) and hands-on experimentation. In the concept invention stage, the MPV groups used the computer simulations developed by Thomas Greenbowe to explore and learn about voltaic cells. They also manually built the voltaic cells, determined the direction of electron flow, and connected the macroscopic feature of the metal electrodes with the concepts of redox reactions. In the application stage, students investigated how concentration impacts cell voltage. They also devised ways to increase the cell potential between iron, magnesium, and copper. Finally, students were given a series of questions that required them to use what they learned and apply it to new situations. As the transcripts of students' discourse were read line by line, we looked at the patterns of who the students talked to, and what they talked about, and whether they included macro, particulate, and symbolic in their discussion. Since we were also concerned whether the lab could be completed within three hours of the lab period, we also looked at how much time students spent in each laboratory activity.

Results

In this paper, we were interested in how MPV students spent time in the laboratory, who they talked to, and what they talked about. We anticipated that the MPV group might take more than 3 hours (180 minutes) to complete the lab activity since students performed both hands-on and computer simulation activities. However, to our surprise, students in this group completed the experiment with an average of 143 minutes. They did not spend the same amount of time in each learning cycle. Most of the time, an average of 42% of the time in the lab or 60 minutes was spent in the exploration stage. We heard much discussion between peer-to-peer and student-to-LI. Students asked their LI to explain the concept and clarify the laboratory write-up. At the beginning of the experiment, the LI introduced the lab experiment and, at the end of the learning cycle, made an explicit connection between the laboratory activities and concepts learned in the chemistry lecture. In the concept invention stage of the learning cycle, students spent an average of 35% (50 minutes) of the time in the lab. Students performed both computer simulations and repeated the same experiment using the hands-on style. While students also talked to their lab partners, they seemed to need help from the LI and we heard the discourse between students and LI more than any learning cycle. The LI discussion at the end of this learning cycle also emphasized the connection between the macro, particulate, and symbolic representations that occurred in this learning cycle. In the last stage, the application, students only spend 23% (30 minutes) of their time completing their lab activity. Students used either the computer simulation or hands-on to build a Danielle cell and answer a series of questions. We did not hear many peer-to-peer or students-to-LI discussions. Most of the discussion between peer-to-peer was encrypted and difficult to follow. The video showed students spend most of their time answering questions in the lab worksheet. The details of how students spent their time in the laboratory, who they talked to, and what they talked about will be presented in the following section.

The Exploration Stage

We were interested in how students spent time during the exploration stage. Who did they talk to, and what did they talk about? Students explored oxidation-reduction concepts through symbolic and hands-on activities. During the symbolic activity, students worked on balancing the charge of an iron metal (Fe), an oxygen gas (O_2), and an iron (III) oxide (Fe_2O_3) (equation 1), and five more equations were given (equation 2 – 6).

$\_\_\_\ Fe(s) + \_\_\_\ O_2(g) \rightarrow \_\_\_\ Fe_2O_3\ (s)$ (Equation 1)

oxidation $Fe \rightarrow Fe^{+3} + 3e^-$ (Equation 2)

reduction $4e^- + O_2 \rightarrow 2O^{-2}$ (Equation 3)

$4Fe \rightarrow 4Fe^{+3} + 12e^-$ (Equation 4)

$12e^- + 3O_2 \rightarrow 6O^{-2}$ (Equation 5)

$4Fe + 3O_2 \rightarrow 2Fe_2O_3$ (Equation 6)

Students talked to their lab partners and their LI. Students discussed the charge of the element in its natural state with their lab partners. Most of these discussions we heard were full of misconceptions. The discussions either created or reinforced the misconception about the charge on an element. Ginny and Luna, like several other pairs of students, thought that the charge on Fe [in its elemental metallic form] was plus three, and the charge on the O atoms in O_2 was negative two.

> Ginny: Oxygen [oxygen gas] is normally two, and Fe [is normally plus three.
>
> Luna: Yeah
>
> Luna: With iron two and oxygen three, is that a thing?

> Ginny: The oxygen charge is negative two.
>
> Luna: Oh, that makes sense.

Ginny and Luna had reinforced each other's misconception about the charge on the Fe and O_2 in their elemental states. Ginny and Luna were not the only pair of students who had a misconception about the charge of the elements in their natural state. Bellatrix convinced her lab partner, Delores, that oxygen had a negative two charge because it appeared on the right -hand side of the periodic table.

> Delores: Oxygen is negative two?
>
> Bellatrix: We learned it was negative two yesterday. On the periodic table, if you look at the end, if oxygen is two from the end [the right-hand side of the periodic table], it got minus.
>
> Delores: Okay …. so, before reacting, iron [metal] will be plus three or three plus for question 1, and oxygen [gas] is negative two or two minus.
>
> Bellatrix: Yeah

Bellatrix's and Delores's discourse was an example of peer-to-peer discourse that created misconceptions. Bellatrix had a misconception about the charge of elements on the periodic table. She thought her professor, in the lecture, said that the elements that appeared on the right-hand side of the periodic table had a negative charge. Her LI passed by their table overheard their conversation, and immediately explained to them that "Oxygen at the elemental state has no charge." We also hear the LI explained to other groups of students, "The charge on the elements form is zero," "Iron at the element state has no charge," and "Oxygen at the element state has no charge." This immediate correction of the misconception seems to help students correct their misconceptions about the charge of the elements in their natural state, as seen during the concept invention stage.

Student-to-LI Discourse. Students also talked to their LI. Students talked to their LI when they could not make sense of the laboratory explanation. Students came to the Electrochemistry lab with various levels of knowledge about the subject, and no matter how well-organized or well-written the laboratory instructions were, students sometimes needed the LI help to bridge the gap between what they knew and what they needed to know. Bill worked on answering the question, “What has to happen to iron’s electrons as it goes from iron metal to rust?” Bill could not understand why when iron metal rusted (Equation 1), it lost 12 electrons (Equation 4), He thought it only lost 3 electrons (Equation 2).

> Bill: Dr. P, I have a question. This one, when iron metal rusted, I do not get why iron loses 12 electrons.
>
> Dr. P: You go from iron metal to rust.
>
> Bill: It loses three electrons
>
> Dr. P: Yes
>
> Bill: But oxygen gains two electrons.
>
> Dr. P: But not really, right? That was a charge on oxygen, but if you look at the way it balances, let’s skip.. skip…skip,.. down here. Actually, iron has to lose 12 electrons, and oxygen has to gain 12 electrons; once I get it balanced. For each individual ion, it loses 3 electrons: that’s true. That's

> perfectly fine, but in order to get it balanced, you have 4 irons. So, 4 irons lose 3 electrons each. That is 12 and 6 oxygens gain 2 electrons each for a total of 12 electrons.
>
> Bill: So, for this one. We are right to say that iron loses 3 electrons.
>
> Dr. P: Yes, each iron is losing 3 electrons.
>
> Bill: Okay.

Bill interpreted the question, “What has to happen to iron’s electrons as it goes from iron metal to rust?” as how many electrons each iron lost as it went from iron in its elemental metallic form to an ion form. He did not see that if he balanced the reaction in Equation 1, he would get the same answer as written in Equation 6, as pointed out by his LI, “ …. but if you look at the way it balanced, ………. Actually, iron has lost 12 electrons [Equation 4], and oxygen has to gain 12 electrons [Equation 5] …” Even, after the explanation of the LI, Bill still said, “We are right to say that iron loses 3 electrons.” His LI had to emphasize. “Yes, **each** iron is losing 3 electrons,” before he agreed with her.

It is difficult to know how students interpreted the explanations, the instructions, or the questions of the laboratory procedures. From the experts’ viewpoint, students should get the correct answer if they follow Equations 1 to 6. However, from a student’s viewpoint, for example, in Bill's case, by himself and without help from his LI, he could not see the connection between Equation 2 and 4.

Peer-to-Peer Discourse During the Hands-on Activity. The peer-to-peer discourse was short and centered around the laboratory setup. Students’ discussion focused on the macroscopic description of matter. Students could identify what is being oxidized but did not give further explanation. Two examples:

Luna: So, we drop zinc into copper, right?

Ginny: Look!! How it [zinc] turns black and crusts up, it's grotesque.

Delores: Hey, did you have a reaction in this one?

Luna: No

Delores: Which one reacts?

Ginny: Zinc plus copper sulfate.

Luna: Yeah

Ginny: I'm not sure which one is a spectator. Obviously, zinc is being oxidized.

Luna: Yep, the zinc's being oxidized…. So, is the sulfate a spectator?

Ginny: Yep.

Another example between Molly and Katie: Molley looked at the piece of a meal and said,

Molly: Yeah, this's zinc.

Katie: That's zinc. Now what do we do? Do we use the full strip?

Molly: I guess, just in case, I would. Dr. P. do we use the whole strip of zinc?....

[later on]

Susan [students from another group]: Did you have a reaction in the zinc one?

Molly: Yeah, the zinc is being oxidized.

Katie: Which reaction does occur [reads the question]?

> Molly: The zinc plus copper sulfate. I am not sure which one is a spectator and which one is being reduced though? Zinc is being oxidized.
>
> Katie: Yes, zinc is being oxidized.
>
> Molly: I don't know which is a spectator and which is doing the reducing.
>
> Katie: Sulfate is a spectator.
>
> Molly: Both of them have sulfate? …I think sulfate is a spectator. The copper was reduced, right?

Luna and Ginny used the macroscopic description, warm, and turn black, to describe their observations. Ginny identified zinc as being oxidized without further explanation. They did not talk about what was being reduced. Katie and Molly had a short discussion about the setup. They did not describe what they observed. Even though the laboratory questions were written to make students think beyond macroscopic features (i.e., "What do you observe?" "Which reaction occurs?) by asking students to identify what is being oxidized and what is being reduced. Katie and Molly quickly identified zinc as being oxidized but did not offer any explanation. They were unsure what was being reduced, and when Molly said, "The copper was reduced, right?" it was difficult to say whether she referred to copper in its elemental form or copper in the ion form.

Students-to-LI. The discourse between LI and students of the same activity sounded very different. Bill and Fleur's discourse at the beginning of this hands-on activity was like the other groups. They talked about lab setup and used macroscopic descriptions to describe their observations.

Bill: Copper (II) sulfate is a solid?

> Fleur: Solution
>
> Bill: So, I guess put in the water?
>
> Fleur: They should have a solution over there.
>
> Bill: I saw the solid back there.
>
> Fleur: That’s the blue thing [blue thing referred to copper (II) sulfate solution] ... Do you have to bend the zinc one or…. It didn’t say.
>
> Bill: I’m going to bend mine.
>
> Fleur: I’m not going to bend mine.
>
> Bill: All right, see, mine has a reaction.
>
> Fleur: What!!!
>
> Bill: See, mine got a reaction.
>
> Fleur: No, it not …. What… no reaction here.
>
> Bill: No, that’s not good.
>
> Fleur: No, buno…. Yours looks like it (is) rusting…. I’m done talking about yours.
>
> Bill: What color is this part?… Looks like silver.
>
> Fleur: Yeah
>
> Bill: This is definitely rust. Which reaction occurs?

Then Fleur and Bill did not know what was being oxidized, so they asked their LI for help.

> Fleur: Which one oxidized? Zinc, right?... It asked which one is being oxidized?
>
> Bill: Dr. P, we’re trying to figure out which one is being oxidized?

LI: Yes, that reaction looks good.

Bill: Nothing being oxidized, right?

LI: This goes from being what charge?

Bill: Nothing

LI: Nothing… what's the charge on zinc in zinc sulfate?... You guys should know by looking at which one actually does something.

Fleur: This goes from zero to plus 2 [referred to zinc metal to zinc ions].

LI: Yes, you're on it.

Fleur: Those two don't have a charge because they are regular solids [referred to zinc, and copper metals], but these are ions.

LI: She [Fleur] said this has zero, and it goes to two [$Cu \rightarrow Cu^{2+}$].

Bill: So which is being oxidized?

Fleur: Zinc is being oxidized from zero to positive two.

Bill: Copper is being oxidized

Fleur: What's being oxidized?

Bill: Copper because zinc is gaining electrons.

Fleur: It [zinc] goes from zero to positive.

Bill: It's losing electrons? So it's oxidation?

Fleur: Zinc goes from zero to plus two. It loses two electrons. Copper goes from plus two to zero; it gains two electrons.

Bill: So oxidation is the loss of electrons, so zinc is being oxidized.

Fleur: Yes

The LI reminded Bill and Fleur about the concept they explored during the symbolic activity (i.e., what charge on zinc in zinc sulfate?). When Fleur replied, “This goes from zero to plus 2”, and later on she said, “Those two don’t have charge because they are regular solids, but these are ions,” revealed that LI alleviated students’ misconception about charges of the element in its natural state. The LI also prompted Bill and Fleur to think about changing in charge (symbolic) and how it is connected to the concept of losing and gaining electrons (particulate) and how these concepts help them identify which metal electrode was being oxidized. However, part of this discussion revealed another misconception. Bill interpreted that zinc going from a charge of zero to a positive two charge means zinc gained two electrons. Fleur had finally convinced him that going from zero to positive two charge means zinc lost two electrons.

The LI Led the Discussion. The LI connected the macroscopic observation and the particulate and symbolic difference from the peer-to-peer discussion. During the macroscopic activity, without the LI’s help, students’ discourse was short, dominated by the macroscopic discussion, and focused on answering questions. Although they could answer the particulate and symbolic questions, they offered little insight into how they made the connection between them. With the help of LI, students’ discourse was longer than without the LI. The connection between symbolic and particulate was well explained, but the connection between macroscopic and symbolic and particulate representations was still unclear. Students seldom think about the connection between macroscopic observations and the explanation at the particulate level. Students saw the surface of zinc turn black and crush up, as stated by Ginny, but they did not make an explicit connection between this macroscopic observation and the chemistry that happening at the surface. The LI explained this connection.

> LI: Zinc and copper. Zinc in copper solution. How do you know that one's favor?
>
> Harry: Because it happens.
>
> LI: What's the sign that ... that one happened?
>
> Harry: Color change
>
> LI: [repeat] Color change…
>
> Harry: You see bubbles.
>
> LI: You see bubbles, and heat, and bubbles are actually from a secondary reaction. Nothing up here is a gas, right, but we do have - usually when we make solution -- heat what types of reaction?
>
> Lilly: Exothermic
>
> LI: Exothermic, energy is a product, okay. Now, where is this exchange happening? It's a single replacement reaction, but it's also an oxidation-reduction reaction. Where is the exchange happening between the electrons of ....[wait for student(s) to explained]
>
> Lilly: Zinc
>
> LI. Zinc! Zinc loses electrons, and what gains electrons.
>
> Lilly: Copper
>
> LI: Copper ions. A bonified reaction is between zinc metal starting with zero and copper (2+) aqueous. What role does sulfate play?

Lilly: A spectator.

LI: Spectator... okay. It's important that they are there but a lot of time, they are not reacting. They are not changing. So, zinc reacts with copper (2+). Zinc is oxidized and copper (2+) is reduced.

LI: Where is the change of electrons happened?

Lilly: On the surface of the metal.

LI: Yes, on the surface of the metal where the metal is touching the liquid, so that exchange is happening right here. If you leave it (the vial that contains zinc and copper) sit for while you're working through the rest of the lab. You'll see some more change just happen. Over time what should happen to the zinc strip?

Harry: It's broken down.

LI: It's break down that's right. If you add enough copper (II) sulfate it will break all the way down - the whole thing. What's going to happen to the copper ion in the solution? What will it turn into?

Lilly: solid

LI: It'll turn in solid copper and as it turns into solid copper. What's going to happen to the solution?

Lilly: It'll clear up.

LI: It'll clear up. … We will rearrange this reaction to see if we can make the exchange of electrons happen across the distances through the wire. Any physics major will be frustrated because a physicist talks about the circuit in the exact opposite of chemist. We're all about what electrons are

> doing. Where do the electrons go? In which direction do they flow? …. In the next part of the experiment, we'll first play with simulation. You're going to have something like this [show the picture on the computer screen]. The simulation will allow you to choose the metal and solution and repeat with different metals and solutions over and over again….

The hands-on laboratory style could be powerful in demonstrating the macroscopic phenomena however, students, on their own, might not think beyond the macroscopic feature. Having the LI lead the discussion at the end of the learning cycle communicated to students what is the intended learning outcome and what students should have learned when they completed the lab activity. The LI also made an explicit connection between the macroscopic observation and the theory students learned in the chemistry classroom, and a connection between the macroscopic, particulate, and symbolic representations. Furthermore, it is a way to make a transition from one learning cycle to the next.

The Concept Invention Stage

Students spent an average of 35% (50 minutes) of the laboratory time in this learning cycle. Students talked to their lab partners about the direction of electron flow (particulate representation), how to write half-reaction (symbolic representation), which ion was a spectator, which metal electrode got smaller or larger, and where oxidation occurred in the electrochemical cell. Students also talked to the LI, asking for help writing half-reactions and explanations about spectator ion.

Peer-to-Peer Discourse about the Macroscopic Features of the Metal Electrodes. During the computer simulation activity, students observed the flow of electrons from one side of the metal electrode to the other side. The computer simulation also displayed the particulate views of the ion exchange between metal electrodes and its solution (i.e., silver electrode in silver nitrate solution). Four themes emerged from the peer-to-peer discourse: (i) students used the concepts of losing and gaining electrons to justify which metal electrodes got smaller and which got bigger; (ii) students could predict which species was a spectator, but they struggled with writing half-reactions, (iii) students had a misconception relating electrons transfer and charge of ions, and (iv) neither hands-on or computer simulation activities help explaining why the metal electrodes are placed in the solution with ions of the same element.

The discourse between Ginny and Luna, Bill and Fleur, Delores and Bellatrix, and Molly, Katie, and Susan, were similar and centered around the loss and gain of electrons as an indication of which metal electrode got smaller or bigger. Some groups of students used the word "particle" instead of "electrons" flowing from one of the metal electrodes to the other. Some students had a misconception that if elements gained electrons, they became positive ions, and all three groups had difficulty with writing half-reactions.

Ginny and Luna:

> Ginny: Which metal's getting smaller? It shows particles coming onto the silver and particles leaving from the surface of copper. Copper got smaller because it flowed from copper to silver.
>
> Luna: First reaction: copper is getting smaller. Copper goes to copper two plus.
>
> Ginny: So, it's like copper has no charge but it gains two electrons and turns into copper two plus (Cu^{2+}).

Luna: Silver then, this one's getting bigger. Silver aqueous plus one gains one electron turns to silver solid [$Ag^+ + 1\ e- \rightarrow Ag(s)$].

Ginny: To me, it's like the opposite.

Luna: Yeah, because you gain electrons on this side,

Ginny: Yeah

Ginny had a misconception that if elements gained electrons, they became positive ions.

Bill and Fleur:

Bill: Each cell in the simulation reacts, which half-cell shows the metal getting smaller?... I didn't notice.

Fleur: Okay.

Bill: I guess we're doing it again. Silver nitrate and copper nitrate… copper's getting smaller.

Fleur: I would think so. This one is losing and this one is gaining.

Bill: Write the metal that got smaller in Cell A. Copper's getting smaller.

Fleur: But they all do that. This one over here always get smaller in all of this.

Bill: You sure?

Fleur: Yeah…. Oh, well, I am not positive.

Bill: So, write a half-reaction for each cell.

Fleur: I don't know, what is a half-reaction?

Female student: Hey, did your guy got through half-reaction?

Fluer: We’re doing that part.

Female student: We have like Cell A, a copper got smaller.

Fluer Yeah, I got that part, but they ask to write half-reaction…

Delores and Bellatrix:

Delores: Which set of half-reactions above represent oxidation occurring in the half-cell?

Bellatrix: For all of them or for one?

Delores: Oxidation would be… gaining?

Bellatrix: Oxidation means losing electrons.

Delores: No, it is gaining.

Bellatrix: No, reducing is gaining.

Delores: You’ve just told me oxidation is zinc. The one that is losing electrons.

Bellatrix: They’re losing electrons. This set is smaller. They are losing electrons and going to the other side…. You know what I mean.

Delores: Losing electrons would be the ones oxidizing?

Bellatrix: They are getting smaller. That would be the first set; the ones in Cell A

Delores: So, the first set is losing, and the second set is gaining.

Molly and Katie:

Molly: So, electrons go from copper over to silver

Katie: Yeah

Molly: Electrons flow from copper to the silver.

Katie: What is(does?) cell potential mean?

Molly: Oh, I have no idea…. What's cell potential mean?

Katie: I think cell potential is voltage. It shows right there [on the computer simulation screen]; we didn't pay attention.

Molly: That's 1.10, and everything's moving to copper….. Why do you think we put metals in solutions with ions of the same element? I don't have any idea. Unless you want to look(hook?) them up, I'll keep doing this.

Katie: I googled it. It said that because metal usually makes positive ions when the compound is dissolving in solution.

Molly: That explains metal and metal, but I don't know metal with the same one. Maybe if we put zinc with silver, it will always be transferred silver with zinc, that might mess up what's going on. Do you know what I mean?

Katie: That may be it.

Molly: So, I have to redo all of them and see which one is getting smaller and larger. In this one, the zinc got smaller, and the silver got bigger. It shows particles coming out to silver and particles leaving from this end.

Katie: Got you.

Molly: I think you do half-reaction. Like zinc goes here, and…

Katie: Cells A and B, right?

Molly: I am doing it right now because I didn't know what we have to look at the things.

Katie: So, zinc is getting smaller. Let me guess; copper's going to get bigger.

Molly: I think it's going to be like that on every one of them. So, zinc got smaller cause electrons were leaving from zinc over to the other side.

Katie: Right

Molly: So, it should be copper gotten smaller.

Susan: Silver got bigger, right, and copper got bigger in this first one.

Molly: No, copper got smaller because it flows from copper to silver. Copper got smaller, and silver got bigger.

Katie: We have to write a half-reaction for all of these. She said you can leave out a spectator thing and just copper and zinc or whatever it is.

Molly: I though half-reaction is zinc with zinc and copper with copper. So, when it's a half-reaction, it's only like copper with copper, like when we do the think like yesterday.

Katie: So, it just be like copper with copper solution?

Molly: I'm not totally sure.

Susan: Will that be this plus that?

Molly: It'll be copper plus copper ions…. See I don't know… So, I'm not totally sure because… like silver and copper switch charges, and they don't have charge, and it's not going to be like Cu to Cu. [I think the student compared the molecular equation to the half-reaction]……… Dr. P I have

> a question about half-reaction. It said to leave out like the spectator ions. Would it just be like when we do the copper. It just likes Cu2+?
>
> LI: No, it’s copper (Cu) goes to Cu two plus (Cu2+) plus 2 electrons. It’s a half-reaction. It shows electrons, got it?
>
> Molly & Katie: Okay
>
> LI: The one that’s getting bigger is silver, right? So, silver ion picks up an electron and make silver. A half-reaction is like that. [she wrote Ag+(aq) + 1e- → Ag(s)].
>
> After LI left,
>
> Katie: You got to see which one’s getting smaller and which one’s getting bigger out of each reaction and then you just write half-reaction. Like solid goes aqueous plus electrons.
>
> Molly: Like the copper has no charge at first, but it gains 2 electrons, so it turns into copper with plus 2 charge.
>
> Katie: So, whatever is gaining it will be on the product side of this one, and this one will be on the reactant side.
>
> Molly: Because this side gains electrons since it’s getting bigger.
>
> Katie: Yeah.

The peer-to-peer discourse showed that students see the connection between the particulate views from the simulation and the macroscopic view (i.e., changing the size of the metal electrodes) even though the differences in size were not obvious in the simulation. Delores and Bellatrix were the only group of students that included all three representations (symbolics - definition of oxidation and reduction, particulate – losing and gaining of electrons, and macroscopic – metals got smaller or bigger) in their discussion. However, all four groups struggled with symbolic representation (i.e., writing half-reactions). Although the example of the half-reactions was given in the Exploration stage, none of the students referred to it. We also saw the interactions between LI and students. When Molly and Katie got frustrated about writing half-reaction, they asked the LI for help. With the help from the LI, Katie and Molly could write the half-reactions. We also found that after watching the simulation, students could not answer why they put metals in solution with ions of the same elements. Katie Googled the answer, but the only information she found was, "Metal usually makes positive ions when the compounds are dissolved in solution." That answer did not help Katie and Molly answer the questions. They finally asked the LI.

> Katie: Hey, what is the answer to question #8?
>
> Molly: We still don't know.
>
> Katie: I can ask her [the LI] about this. I really want to know. Dr. P, we need help. Dr. P why do we put metals in the solution with ions of the same element?
>
> LI: When we put copper in the silver solution, what happens?
>
> Katie: It would react.
>
> LI: That's right. It would react directly. Will we get the current flow through that write?
>
> Katie: No

LI: No, all the reactions happen in the beaker. However, when we put the metal in the solution of the same kind, we know we don't get the direct reaction and force electrons to go through the external wire.

Molly: Oh, that makes sense.

LI: That makes so much sense.

A similar discussion occurred between the LI, Bill, and Fleur.

Bill: I don't know why we put the metal with ions of the same element. Dr. P, I tried to listen to what you said about this one, but I still don't understand.

LI: Okay, if I build the cell. I built the cell [click on simulation] where I put silver in copper solution and copper in silver solution. What happens?

Fleur: Nothing.

LI: Nothing in the cell. What's happening here?

Bill: Silver and copper react.

LI: Do you see the solution getting blue?

Fleur: Yeah.

LI: Okay, so what I have in here is I have a direct reaction just like the one you did minutes ago with zinc and copper [referred to previous hands-on activity]. The direct reaction happens here. Except this time, it's eating up the copper and making silver, and why is there nothing through the voltmeter?

Fleur: It was because... the metal was not in the solution of the same ion.

LI: So, since it is the solution that can react with there is no reason for electrons to travel over here to react with the solution on this side, right? It

> doesn’t want to react to this solution. This is the copper solution. Why would electrons travel from copper to copper when they have silver right here that they can react with? If a direct reaction can happen, it will and won’t bother going through here to make the reaction occur.
>
> Fleur: So, you put it in the solution of the ion so that it has to go through.
>
> Bill: So, it has to travel.
>
> LI: You avoid the direct reaction, so you force it to react through the close circuit,
>
> Bill: Oh

Though the computer simulation showed what happened in the cell at the particulate level, it did not provide an explanation of why things happened the way they happened. The LI played an important role in filling that gap. The discourse between the LI, Molly, and Katie, and LI, Bill, and Fleur proved the point.

Peer-to-Peer Discourse During the Hands-on Activity. After completing the simulation activity, students built the same Daniell Cell manually. During this activity, students focused on the macroscopic features. We examined the peer-to-peer discourse from three groups of students: Group 1, Ginny and Luna, Group 2, Delores and Bellatrix, and Group 3, Molly, Katie, and Susan.

> (Group 1)
>
> Ginny: Which of the three cells produces the largest positive voltage? I think copper has the least potential. I think zinc has more potential than silver, but silver has more potential than copper. Because when copper with silver it’s only 10. I think it has to be zinc, silver, and copper.

Luna: No, it has to be zinc, copper, and silver.

Ginny: But copper has the least cell potential. I said Zn +Ag make the best cell; Zn and Cu make the second best, and Ag + Cu make the third best. Anything the copper is related to is worse than Ag or Zn. So Ag and Cu and make the worst according to the reactivity series.

Ginny: What is a reactivity series? Oh, here it is. So silver is the lowest [they use the activity series to predict.]

Luna: Look here; electrons flow from zinc link(?) here twice and the copper here once but never silver. Silver will be the lowest reaction.

(Group 2)

Delores: I think we have to do 3 batteries.

Bellatrix: Do we have to make it like iron, Mg pair?

Delores: Not .. wait.. iron and magnesium in one battery and iron plus copper in one battery, and copper and magnesium in one.

Bellatrix: Which one is the most reactive? Magnesium will be the one that’s the most reactive. So, we need to do magnesium and copper. That’s what we need to do?

Delores: Why don’t you do iron with..?

Bellatrix: Magnesium and copper? If you see here, the highest cell potential is zinc and silver because they are further apart from the reactivity table.

Delores: Does that matter?

Bellatrix: I think so because here the lowest is copper and silver, and they'er right next to each other on the table. And zinc and copper are a little bit further. Zinc and silver are the further.

Delores: What happened?

Bellatrix: Let's do one more magnesium and copper, then. So, let's do the magnesium one.

Delores: Where do you get copper and magnesium at?

Bellatrix: If you look at the activity thing. The ones that are further apart are the most reactive. That is why silver and copper didn't react very much. So, it will be magnesium and whatever…

Delores: Copper and magnesium, right, so then we do magnesium and magnesium and copper and copper…. 1.65

(Group 3)

Molly: So apparently zinc and silver are really reactive because it has the biggest cell potential.

Katie: Mmm.. Mmm

Molly: Anything copper is in it has less potential. I think zinc has more potential than silver, but silver has more potential than copper. Because when copper is with the zinc, it was higher, too, and then …

Katie: Rank the metals from most reactive to least reactive. It'll be zinc.

Molly: I think it is silver, no, no zinc, silver, and copper

Susan: No, it will be zinc, copper and silver.

> Molly: But when it is copper, the cell potential both times is smaller when copper's involved. But, when it was zinc and silver, it had the highest cell potential. You feel me?
>
> Katie: I don't know.
>
> Susan: I don't know. We'll find out. The metals are also found in the Activity Series.
>
> Molly: Don't forget how we decided on the relative ranking. I said Zn and Ag make the best cell, Zn and Cu make the second best, and Ag and Cu make the third best and anything that Cu is related to is worse than Ag and Zn. Because Ag and Cu make the third best. Zinc is more reactive than silver.

Most of the discussion focused on macroscopic representations, voltage readings, and activity series tables. Both Ginny and Molly based their ranking of metal on the voltage reading. Both indicated zinc was the most reactive because the potential difference between zinc and silver was the highest, followed by zinc and copper and silver and copper. Both Ginny and Molly had a misconception that since the last two readings (i.e., zinc and copper and silver and copper) involved copper, copper must be the least reactive metal. Luna was the only one who based her ranking on the particulate views. She ranked zinc, the most reactive, followed by copper and silver as the least reactive. She explained that zinc was the most reactive metal because electrons flew from zinc to silver and copper. Copper is a moderately reactive metal because electrons flew from copper to silver, and silver is the least reactive because no electrons flew from silver. Delores, Bellatrix, and Susan used the activity series table to determine the reactivity of the metals.

The Application Stage

Students spent an average of 30 minutes completing the application stage of their laboratory activity. Students did not spend that much time talking to each other. Most of the discourse was short, encrypted, and difficult to follow, for example, the discourse between Ginny, Delores, and Luna about a voltaic cell of silver metal in a silver nitrate solution and nickel metal in a nickel nitrate solution.

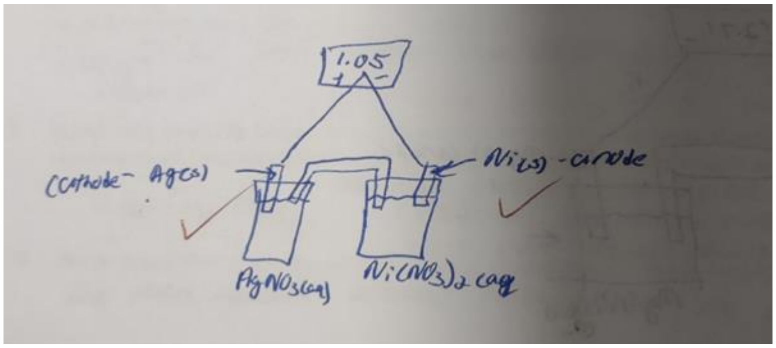
> Ginny: You said nickel.
>
> Delores: We said nickel is oxidizing, and silver.
>
> Luna: Is nickel always oxidizing?
>
> Delores: The thing is, it releases electrons. The way I did it, I am not sure, but I did plus is more likely the thing, and minus is more likely the other thing. I am doing like the magnesium. How negative is 2.37 and set up likely most of them and that one is most likely to oxidize.
>
> Ginny: Yeah, negative is more likely to oxidize
>
> Luna: When electrons are on the left, apparently.
>
> Ginny: So first one – I thought positive is more likely
>
> Luna: She said magnesium is most likely to oxidize, right? So, +2 electrons is on the left and gives us negative 2.37 so that means when e is on the left, it’s oxidizing.
>
> Ginny: Okay.
>
> Luna: It’s not spontaneous, negative is nonspontaneous.

> Ginny: So, silver is being reduced, right
>
> Delores: Ahh .. yes, its gaining. I said it was gaining.
>
> Luna: What you got .75, or .25
>
> Ginny: 1.05

They draw the diagram of the voltaic cell (Figure 10) they discussed but forgot to include the flow of electrons.

Figure 10

Voltaic Cell



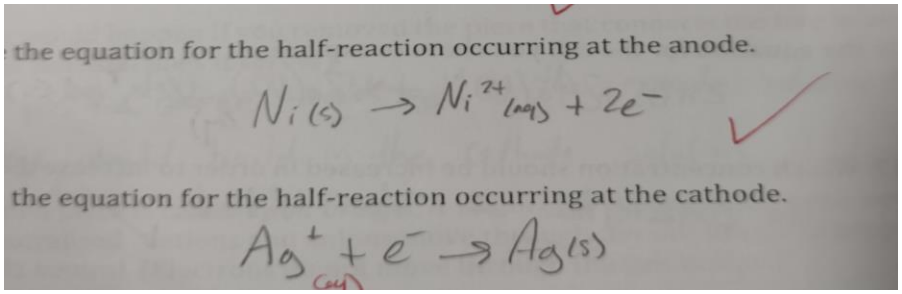
Note. Student diagram of the voltaic cell without the flow of electrons.

The discussion about the half-reactions was also short and difficult to follow, but they wrote the half-reaction (Figure 11) without help from the LI.

> Delores: When writing the overall redox reaction, should both of NO3 be on the same side?
>
> Bellatrix: It should be on the opposite side. Yeah that one
>
> Delores: Since Ni+2 is releasing, should it be on the left?
>
> Bellatrix: Yes, kind of like we did over here. When one gains it should be on the right.

Figure 11

The Half-Reactions and Overall Redox Reaction



the equation for the half-reaction occurring at the anode.

$Ni_{(s)} \rightarrow Ni^{2+}_{(aq)} + 2e^-$

the equation for the half-reaction occurring at the cathode.

$Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

The rest of their work was done with little discourse between lab partners. Some of the true or false questions were answered without explanation, but they completed their work before 3 hours.

Discussion

Assertion: Students begin to build an understanding of the nature of chemistry at all three levels of representation of nature, and it can be accomplished in less than three hours. The overload of working memory during laboratory activities can be mitigated by breaking down laboratory activities into stages, by laying the foundation of the knowledge and the new activity built on the previous one. Following the POGIL design model, in the first stage, the exploration stage, students spent most of their time exploring concepts and making connections between symbolic and particulate representations. Students talked to their laboratory partners and their instructors. The peer-to-peer discussions revealed students' misconceptions about the charges of elements in their elemental state and associated gaining positive charge with gaining electrons. The role of the LI is critical in helping students build a foundation and alleviating the misconception that occurs during this activity. We found students a lot of interaction between students and the LI. Students needed much help from the LI ranging from making connections between various symbolic representations, validating their answers, helping them make connections between the levels of representation, debugging misconceptions, and solidifying students' understanding of concepts. During the concept inventions, students spent an average of 50 minutes and performed both particulate and hands-on activities. Students talked a lot with their peers. The types of laboratory activity determined the type of talk, macroscopic activity (i.e., hands-on) resulted in the macroscopic talk, and particulate activity (i.e., computer simulation) resulted in particulate talk. Students could answer the macroscopic questions, such as bigger or smaller, however, seeing the particulate views does not guarantee that students will be able to answer the particulate questions. While watching the flow of electrons and the exchange of electrons and ions at the surface of the metal electrodes, without help from the LI, none of the students could explain why they put the metal in solutions with ions of the same element. Which admittedly is a more complex question not derived strictly from the picture. Once again, the role of LI is more than to monitor the safety of students in the laboratory. The role of LI is to help students connect the laboratory activity and the underlying concept behind the activity and to guide the students from what they know and what we want them to learn. During this activity, the peer-to-peer talk revealed that students started to make connections from particulate (view the simulation) to macroscopic (answer macroscopic questions) representations and often used the concepts of the changing charges from metal at the natural state to ions (symbolic representation) as part of the discourse. We also found that the LI corrected students' misconception about the charge of the natural element, but we also heard students equate going from zero to positive charge to gaining electrons. We still heard much interaction between the LI and students during this activity, but the interaction between the LI and students was minimal when students worked on the application stage. They spent an average of 30 minutes answering questions. The peer-to-peer was infrequent, and the discussion was short and difficult to follow. However, when examining their works, they could connect various forms of symbolic representation, which they had a problem with at the beginning of the laboratory activity, and they could answer the particulate questions without having to perform a particulate activity. The activities that we thought might take more than three hours were completed within two and a half hours on average.

We were able to design laboratory activities that excited students, promoted particulate talk, and finished within three hours. The laboratory discussion should include all three levels if we want students to think at macroscopic, particulate, and symbolic levels. Having experienced LIs will increase the effectiveness of learning in the laboratory. Experienced LIs can help students bridge the knowledge gap and guide them to think beyond what they can accomplish alone. LI helped maintain students' positive attitude in the laboratory (e.g., if students do not understand something in the lab and they are left without help, they can get frustrated). When designing and implementing laboratory courses, not only must we think about the laboratory activity, but we must think of how to properly train the LI beyond keeping students safe.

Conflicts of Interest. There are no conflicts to declare.

Acknowledgements

The authors would like to acknowledge the help of Dr. Phelps who made this project possible and who not only allowed me to access her students but also agreed to teach both lectures and labs in this study. I would also like to thank the students involved in the study who were willing to let me listen in on their conversations.

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CHAPTER 5: DISCUSSION

Chemical educators often turn to the laboratory as the potential solution to students ‘learning difficulties in chemistry. However, with the increasing cost of running a laboratory program, it is more important to take a hard look a the chemistry teaching laboratory and what happens there. Can we implement cost-effective laboratories in the general chemistry course that help students learn chemistry by promoting conceptual understanding? Can introductory laboratories help students think in multiple representations, and can it all be done within three hours of block time?

What we learned was that the type of visualization heavily influences the discourse in the laboratory. The type of visualization offered in the laboratories students engaged in impacted whom they talked to and what they talked about during the Electrochemistry laboratory activity. For the traditional hands-on laboratory, macroscopic visualization (MV) is the prominent visual mode of learning, while particulate visualization (PV) is the prominent visual mode of learning for the computer simulation laboratory. The data show that the students in the laboratory where visualizations are macroscopic attend to macroscopic things like color, texture, and meter readings. The MV gave students firsthand experiences with chemical reactions that, based on their verbal expressions of excitement from the audio tapes of “cool”, and “wow’, engaged them in the activity. However, the students don’t readily demonstrate that this mode of visualization is leading them to a deeper understanding of Electrochemistry concepts, in part because so much of their discourse focuses on reading and interpreting procedures, and setting up equipment, leaving only 12% of their time in the laboratory engaged in peer-to-peer discussion of the laboratory results. The interactions MV students did have with their peers were generally short, with little or no negotiation of ideas between lab partners. These results, however, do not mean macroscopic visualization has no place in developing a conceptual understanding of electrochemistry. The discourse between the TA and students showed that, with careful questioning and guidance from the TA, the students were able to evaluate their data and apply their findings to new situations and were able to order the reactivity of metals correctly. We want students to be excited about chemistry and develop a macroscopic practical understanding of concepts. For example, the macroscopic visualization was powerful for driving home macroscopic questions, such as which electrode loses mass in a galvanic cell. The particulate visualization (PV) students talked to each other more than the MV students did and more of that discussion involved interpreting the results of the data collected. Unlike MV groups, where physical phenomena seemed to be the highlight of the experiment, the PV groups, while fascinated with the display of chemical reactions at the particulate level, seemed to focus more on the concepts and interpreting what was happening at the particulate level. While these groups of students provide rich information on how particulate visualization influences how students construct their understanding of Electrochemistry, they also reveal various misconceptions. When given these particulate level visualizations, students are cued to try to provide particulate explanations for even macroscopic questions like which electrode gets smaller. Because of their relatively low engagement with the teaching assistants, PV students were not always challenged when they developed alternative explanations that led them to correct answers. This would indicate that the particulate visualization alone is somewhat lacking in helping students develop a complete understanding of chemical processes.

As we combine the laboratory experiments that included both PV and MV (i.e., mixed method), the concept of oxidation-reduction reactions was introduced through symbolic representations (i.e., balancing molecular and redox reactions). Students needed clarification about the charge of elements in their natural stage but were corrected by the laboratory instructor (LI). They also needed help from LI to explain the transition from one symbolic form (i.e., molecular equation) to another (i.e., oxidation-reduction equations). However, once the concept of losses and gains of electrons through oxidation-reduction reactions was introduced, they used this concept to connect macroscopic and particulate representations. During the hands-on procedure, the MV was still a dominant topic of discourse. The discourses were shorter and focused on visible characters. However, the experience with the macroscopic feature helped these groups of students connect between particulate and macroscopic representations. When the experiment moved from MV to PV, students could answer which metal got smaller and which got bigger. During the PV, students also talked more about the concepts and interpreting what was happening at the particulate level, but they also spoke across multiple levels of representation. While peer-to-peer discourses talked about oxidation /reduction and jumped to the concept of gain and loss of electrons and macroscopic features big and small and connected to writing half-reactions, the discourse led by TA gave an explicit connection between macroscopic, particulate, and symbolic representations and vise versa. While peer-to-peer talked about the losing and gaining of electrons at the surface of metals equated to the change in the physical appearance of metals, the TA made a clear connection between MV (i.e., changing in color, bubble, forming precipitations) and PV (i.e., the exchange of electrons at the surface of metals) and how it equated to the physical change of the metals. As the lab continued, students in this group spent less time completing both MV and PV activities. For the same laboratory procedures, the MV group spend an average of 125:92 min to conduct the hands-on experiment; the PV group spend an average of 88:53 minutes to complete the computer simulation experiment. The mixed method group spent an average of 142:92 minutes instead of 214:45 minutes to complete both MV and PV activities. The activities that should take more than three hours were completed within two and a half hours. Students in this group spent more time in the exploration and concept-building stages. As they started seeing the connections between representations, they were better equipped to complete the activities independently of their laboratory instructor.

The activity the students were engaged in heavily influenced what students discussed. These trends are important for us to know---it is important for those designing laboratories to decide what we want students to get from the laboratory experience and design accordingly. If we believe that the multiple representations, as explained by Johnstone (1983), are important for the learning of chemistry, then we need to think about how to use the laboratory to help students make these connections. The laboratory should be a place of excitement, where students get a macroscopic sense of chemistry and a WOW factor which was the case for these students. However, chemistry is also about the particulate understanding, and since the explanations for most of what students observe at the macroscopic level lie in the particulate level. We can bring the best of both worlds and complete the activity within the three hours block if students have time to explore the concepts and build connections among representations. However, Laboratories, no matter how well designed, can only partially instructor-proof. The laboratory instructor is critical to the student's success. The discourse between the TA and students showed that, with careful questioning and guidance from the TA, the students could evaluate their data, apply their findings to new situations, and help them see the explicit connections between representations, and therefore who teaches lab and how we prepare them is critical to student's success.

If we want laboratories to be places where meaningful learning occurs (and therefore, worth the money and time spent), we must be more explicit with our objectives and more precise in our design. These data indicate that the type of visualizations we provide the students influences what they think about even when answering the same questions. At many institutions, the laboratory has remained fairly unchanged for decades, focusing on techniques of data collection and macroscopic observations of chemical phenomena. These types of activities pique some students' interest and provide excitement about chemistry, but we can do more. A large block of time is carved out for this laboratory experience, and there may be a way to keep the macroscopic benefits while capitalizing on the unused time to enhance particulate understanding.

The Future of Laboratory Education Research

We started out trying to understand the role of the hands-on (MV), the computer simulation (PV), and the combining of the two styles (MPV) of the laboratory and what is possible for students to learn under each laboratory setting. First, we found that the MV provided the macroscopic view that explained why we saw what we saw in the domain students could connect to. However, students tended to focus on the surface character, such as color changes, rather than the connection between macroscopic display and chemical reactions. It is up to the LI to show students what they should be looking for in the MV activity. The LI impacted students' learning in the laboratory. The LI in this MPV study was an experienced instructor with over three decades of teaching experience and could help students learn in the laboratory beyond what they could do alone. However, most universities use graduate students (GTAs) with little or no teaching experience in teaching laboratories. It will be worth investigating the GTAs' level of teaching experience and the impact on students' learning experiences in the laboratory. This finding will give us a better understanding of our GTA and what type of training they need so they will be better prepared for the task.

Second, the nature of chemistry included three domains of representation (Johnstone, 1982, 1983). In Electrochemistry, all three domains of representations are equally important in understanding the concept, and the MPV lab style is suitable for it. That raised questions about other chemistry topics, for example, acid-base reactions, gas laws, and thermodynamics, to name a few, on what is possible for students to learn in the MV, PV, or MPV laboratory styles and how laboratory styles impact students' learning experiences.

And third, the POGIL activity that we used, started with symbolic representations followed by a hands-on experiment. It would be worth investigating whether the order of representations affects how students construct the understanding across macro, particulate and symbolic representations in the laboratory. Understanding the order of representations and the impact on students learning across three representation levels will help us design a better laboratory curriculum.

References

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