Objectives and Theoretical Framework

Learning science presents unique challenges to the learner with regard to considering invisible worlds, such as molecules and solar systems, as well as developing skills at modeling and representing those worlds. Researchers have underscored the consequences of these difficulties, particularly as experienced in the chemistry classroom. Typically, chemistry instruction asks students to reason how the macroscopic observable realm can be understood through a submicroscopic lens that focuses on the interactions of molecules and atoms. This transition between the macroscopic and submicroscopic levels is indispensable for developing a meaningful understanding of chemical knowledge (Gabel, 1999; Hinton & Nakhleh, 1999). Moreover, this knowledge is often communicated through the use of various representational symbols, such as drawings, molecular models, and equations that constitute the language of chemistry (Treagust, Chittleborough, & Mamiala, 2003). Thus, shifts between the macroscopic, the submicroscopic *and* the symbolic realms require a great level of abstraction and conversion of knowledge forms by the chemistry student (Johnstone, 1993).

While research abounds in studies that catalog students' difficulties and misconceptions in the chemistry discipline (Duit, 2009; Nakhleh, 1992; Taber, 2002), very few studies have been conducted to track the evolution of students' reasoning in the chemistry classroom. Currently, two bodies of literature inform our understanding of students' progression in chemistry over time. The first relates to studies that focus on novice-expert shifts among chemistry learners (e.g., Kozma & Russell, 1997; Stains & Talanquer, 2008). The second pertains to studies that directly examine the effect of particular teaching interventions on students' reasoning and understanding in chemistry (e.g., Georgiadou & Tsaparlis, 2000; Yezierski & Birk, 2006). Both bodies of literature suggest general learning patterns, such as learners' increased ability to attend to implicit submicroscopic features (Crespo & Pozo, 2004; Yezierski & Birk, 2006) and to acquire a more sophisticated ability to work with symbols and models (Dori & Hameiri, 2003; Georgiadou & Tsaparlis, 2000).

Typically, such studies examine the change of students' chemistry understanding through a quantitative analytical approach where change is represented by differences between total scores on pre-post achievement assessments. While informative, such analysis may conceal significant variations and trends in students' reasoning. Other studies have shown that by analyzing student inscriptions and model-use qualitatively, it is possible to see subtle shifts in students' mental models of chemical phenomena (Cakmakci, Leach, & Donnelly, 2006; Harrison & Treagust, 2003; Pallant & Tinker, 2004). It is in this qualitative tradition that we propose a fine-grained analysis of students' pictures and verbal explanations to assessment questions to offer insights into students' developing chemistry knowledge. We accomplish this with an analysis of the micro-changes in student responses to pre-post assessments from a classroom using the Connected Chemistry Curriculum (CCC) (Stieff, 2003). In what follows, we present the methodological steps we adopted in our analysis, as well as the main patterns that we observed in student responses, to characterize the changes in students' understanding of chemical phenomena and in their ability to communicate this understanding before and after instruction. We argue that, while aligned with literature on representational competency in science and chemistry in particular (diSessa & Sherin, 2000; Kozma & Russell, 1997), our findings motivate extending this construct to include both verbal and pictorial modes of communication and coordination between them.

Methodology and Analysis

For the present study, we randomly selected two classes of 45 students from a sample of 41 classes using CCC. The classrooms, taught by Mrs. Fadi (pseudonym), was located in a suburban public school serving a student population that is 95% Black non-Hispanic and 24% on free and reduced lunch. Mrs. Fadi is a female teacher of Middle Eastern decent with 12 years of experience in teaching chemistry. During the beginning of the school year, she implemented CCC, a curriculum that focuses on employing dynamic computer simulations to allow students opportunities to make observations of visual representations of submicroscopic interactions between molecules. Along with the simulations, the curriculum uses guided inquiry workbooks that help to scaffold students' observations of these molecular interactions (Stieff & McCombs, 2006). The present study focuses on student responses to assessment questions from the *Discovering Matter* unit. In the unit, students make guided observations and inferences related to the composition and behavior of submicroscopic particles to classify matter, identify differences between physical and chemical changes, and describe the composition of mixtures. Our data is comprised of student responses to the *Discovering Matter* unit assessment, which is composed of multiple-choice questions from the local school district and questions designed by the curriculum developers to assess students' knowledge of submicroscopic representations. The assessment was administered once prior to the implementation of the unit and again immediately after the implementation.

Initially, we attempted to apply an a priori coding scheme that categorized student responses according to representation level (e.g., macroscopic, submicroscopic, symbolic) and conceptual correctness, to determine the effect of the curriculum. As the analysis progressed, we noticed that our coding scheme did not effectively capture the diversity, richness and complexity of student responses across items. Therefore, we abandoned the coding scheme and employed a constant comparative method (Strauss & Corbin, 2007) to identify emergent patterns with the responses. To do this, we reviewed students' verbal explanations and drawings in response to three specific questions that asked students to produce submicroscopic representations and describe their representations in words (see Appendix A). We limited our analysis to include only students who provided complete responses (i.e., both a drawing and an explanation) to these questions. In total, 28 students provided complete responses. During the first round of review, we annotated noticeable differences between pre- and post- responses to each question. These differences were varied and included changes such as, transitions from drawing macroscopic to submicroscopic representations or transitions from depicting atomic composition alone to depicting both atomic composition and molecular motion. From this process, we identified eight codes that we believe captured specific changes in student responses to all items (Table 1). From these codes, we observed significant changes in students' competency for coordinating verbal and pictorial responses

Table 1
Emergent Codes for Student Responses

1.	Shift from macro to submicro type responses
2.	Shift from discrete to integrated model
3.	Shift from generic to more specific submicroscopic models
4.	Shift from single to aggregate level representations
5.	Shift from macro-submicro drawings to submicro drawings.
6.	Shift from annotated submicroscopic representations with symbols (e.g., H, O) to only submicroscopic representations
7.	Shift in verbal answers that focus on composition towards encompassing both composition and behavior of molecules
8.	No observable change

Results and Discussion

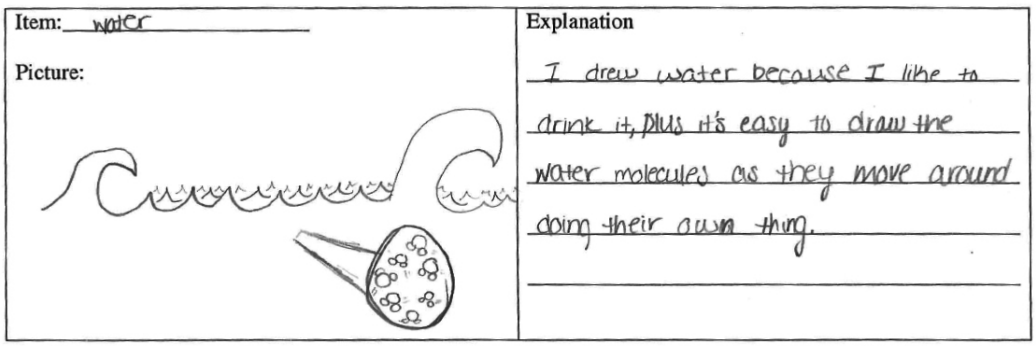
Looking across the codes, we observed students shift from using representations that depicted the macroscopic level to those that depicted the submicroscopic level in both verbal and pictorial answers. Similarly, we observed students employ representations depicting molecular phenomena that were more similar to those used by expert chemists and chemistry teachers. Such changes have been documented in prior studies (e.g., Georgiadou & Tsaparlis, 2000; Stieff, 2010; Stieff & McCombs, 2006; Yezierski & Birk, 2006) and we will not detail them further here. Rather, in the remainder of the paper, we focus our discussion on a prominent pattern of change in students' answers that we believe has been previously overlooked. Namely, we noted a significant change in students' explanation of chemical phenomena by coordinating various modes of communication to express their relational understanding using words and pictures.

We refer to coordination as the way students select different modes of communication to reveal various aspects of their chemical knowledge. For instance, student's initial pictorial representations depicted multiple levels of perspective, while their later pictorial representations modeled the submicroscopic level exclusively and their verbal answers reflected attempts to relate different levels. Even when students included only a submicroscopic representation in their drawings on the post-test, their integrated verbal responses indicate that they were also considering relationships among levels. In general, students included more detailed verbal descriptions on the post-tests accounting for both macroscopic and submicroscopic levels and the relations between them. We hypothesize that this change is related to the way in which submicroscopic representations were presented in the simulations and might imply students develop a more fine-tuned conception of modeling from the simulations. In what follows, we present two different examples from students' pre-post responses that illustrate the change we observed in the ways students communicate their knowledge.

Example 1: Shift from multilevel to submicroscopic pictures, aligned with improved integration of levels in verbal responses

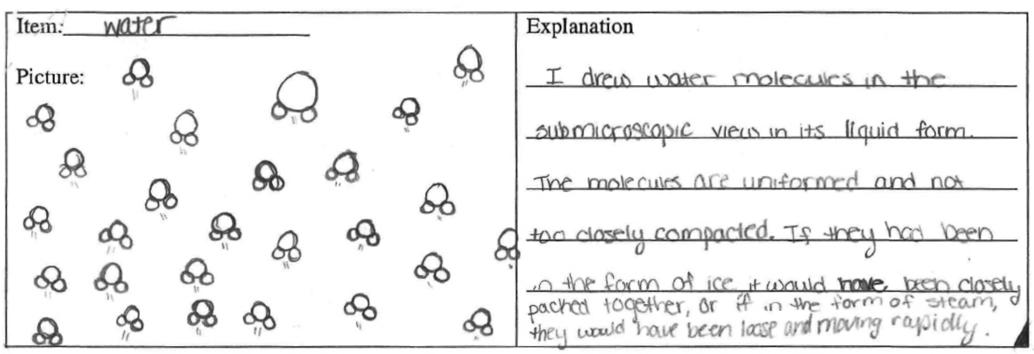
As illustrated in Figure 1, the student's pre-test drawing depicts both macroscopic and submicroscopic features of water; however, when explaining his drawing, the student does not convey a clear understanding of the relationship between these two levels of description. On the other hand, while the post-test drawing focuses on the submicroscopic aspect, the student's verbal explanation communicates a more integrated understanding of the relationship between macroscopic observations of different states of water and the corresponding submicroscopic molecular interactions. It is worthy to note that the shift did not occur at the content knowledge level since the student provides similar details about the structure of water on both occasions. Rather, a more significant change occurs in the student's coordination of the drawing and the verbal response to describe the phenomenon. The student's reference of the three states of matter (i.e. macroscopic level) and their corresponding molecular interactions (i.e. submicroscopic level) demonstrates an ability to verbally express their integrated knowledge of the phenomenon.

Pre



Explanation: I drew water because I like to drink it, plus it's easy to draw the water molecules as they move around doing their own thing.

Post



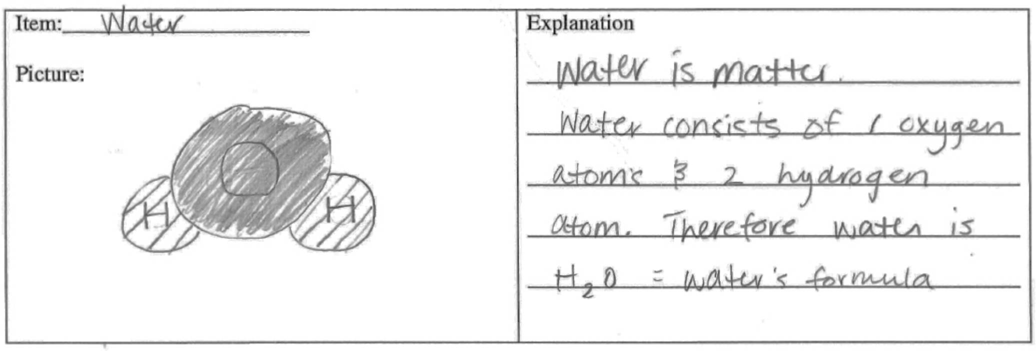
Explanation: I drew water molecules in the submicroscopic view in its liquid form. The molecules are uniformed and not too closely compacted. If they had been in the form of ice, it would have been closely packed together. Or if in the form of steam, they would have been loose and moving rapidly.

Figure 1. Sample of students' work illustrating integration of levels

Example 2: Shift in the way students expressed knowledge of composition and behavior

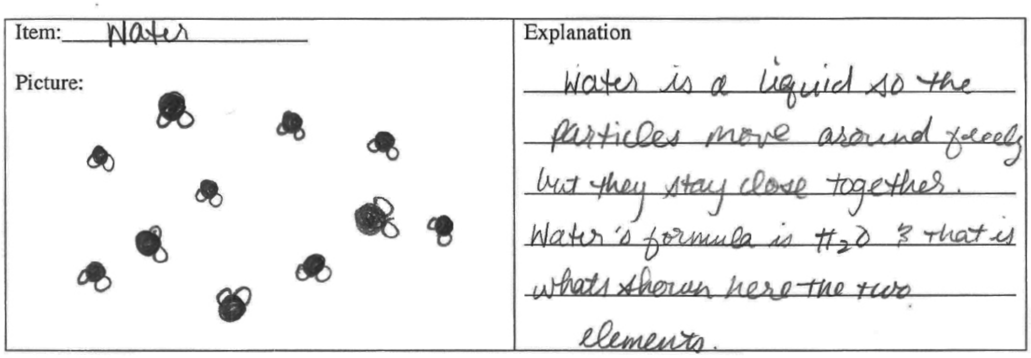
In the pre-test drawing in Figure 2, the student included only one water molecule with symbolic annotations (H and O). Both picture and explanation focused on the compositional aspect of the molecule; namely, that it contains two hydrogren atoms and one oxygen atom. Conversely, the post-test illustration shows a number of water molecules without chemical symbols and represents the relative spacing and orientation of the particles. Moreover, the post-test explanation includes aspects of composition, structure and behavior that are not shown in the picture (e.g., movement of particles, constituent elements). It is interesting to note that in the pre-response, the picture and the explanation mirrored the same content knowledge. However, in the post response, the student's knowledge of the aggregate nature of water molecules is complemented by the verbal explanation of the behavior and composition of these particles.

Pre



Explanation: Water is matter. Water consists of 1 oxygen atoms & 2 hydrogen atom. Therefore water is H_2O = water's formula.

Post



Explanation: Water is a liquid so the particles move around freely but they stay close together. Water's formula is H_2O & that is what's shown here the two elements.

Figure 2. Sample of students' work illustrating a shift of representing composition and behavior

Conclusion

The two examples we detailed above illustrate over developing analysis of features of verbal and pictorial coordination in students' responses. We note that these features are not exhaustive. Morever, we did not observe this pattern for each and every student, nor claim that it necessarily applied to all responses from an individual student. Regardless, our findings indicate that important changes in students' responses occur not only at the content knowledge level, but also (and perhaps more importantly) in students' ability to coordinate and selectively use verbal and pictorial modes of communication to express and represent their knowledge. We hypothesize that the shift towards a focus on only submicroscopic drawings could be rooted in a change in students' understanding of the role and function of models as a tool to represent an invisible and often inaccessible realm. In turn, this motivates further research on students' epistemologies on models and representations in chemistry. We argue that adopting a qualitative microanalysis of the data enabled us to delineate these nuanced changes in students' responses. In sum, our findings resonate with diSessa and Sherin's (2000) conceptualization of meta-representational competence with specific regard to students' understanding of scientific symbols and pictures. As well, the change we observed in students' drawings closely align with the framework developed by Kozma and Russell (1997) to describe chemistry representational competence. While resonating with these frameworks, our findings motivate the need to expand upon both to account for the development of verbal representational competency as well as the ability to coordinate both pictorial and verbal modes of representations. We argue that by considering both aspects together, we gain further insights into students' knowledge and conceptual understanding of chemical concepts.

Appendix A

#1

24. Each of the following items is classified as matter: **air**, **water**, **gold**. Pick one of the items and draw a sub-microscopic picture of the item. Explain, in words, the picture you drew.

Item:______________________ Picture:	Explanation ____________________ ____________________ ____________________ ____________________ ____________________

#2

29. Draw a sub-microscopic picture of a heterogeneous mixture.

Picture:

30. Explain, in words, your drawing for question 29.

#3

33. Water can exist as both steam and ice. Draw a sub-microscopic picture of liquid water, steam, and ice.

LIQUID WATER	STEAM	ICE

Explain, in words, each of your drawings

Figure A-1. Questions analyzed from the *Discovering Matter!* assessments.

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