STUDENT KNOWLEDGE, LEARNING CONTEXTS, AND METACOGNITION: AN EXPLORATION OF THE USE OF CURRICULAR MODULES THAT FEATURE 3-D COMPUTER ENVIRONMENTS OF BIOLOGICAL PROCESSES

by

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(Under the Direction of J. STEVE OLIVER)

ABSTRACT

Studying cognition and metacognition in the classroom poses difficulties for researchers, as they are ambiguous and often mischaracterized in scholarship. Additionally, practical applications are limited, as most of the research tends to be theoretical. Designed around innovative modules that feature 3-D computer environments of biological processes (the modules), this three-part study addresses these issues.

In the first article, students' conceptions of osmosis, diffusion, and filtration were examined as represented by their responses on questions both internal and external to the modules. In-depth analysis of data from six students showed that the modules had very little impact on student knowledge. Additionally, higher scores on forced-choice versus free-response questions indicated rote, rather than meaningful, learning.

In the second article, students' knowledge was characterized over a variety of learning contexts to determine how demonstration of knowledge differs depending on context. Using both qualitative and quantitative data, three students' construction of knowledge at different stages was characterized. Despite fairly consistent test scores, students maintained misconceptions related to molecule movement, concentration gradients, and equilibrium.

The third article focused on metacognition and how the current literature could be incorporated into a new model that researchers could utilize to code think-aloud interview transcripts for cognitive and metacognitive knowledge and monitoring skills. The model that resulted showed promise as both a tool to assess students' learning and instructional techniques and effectiveness. Using the model, researchers will be able to use the concurrent think-aloud protocol in a more effective manner.

INDEX WORDS: Cognition, Metacognition, Educational technology, Science knowledge, Secondary education, Concurrent Think-Aloud Protocol

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A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2013

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August 2013

DEDICATION

This dissertation is dedicated to my daughter, who made this entire process much more difficult than it should have been, and my wife, without whom there would be no dissertation to dedicate.

ACKNOWLEDGEMENTS

Thank you to Steve Oliver, Julie Kittleson, Kathleen deMarrais, and Norm Thomson. For some reason unbeknownst to me, you all trusted that I could deliver a complete dissertation, despite having to change plans entirely. Thank you for forcing me to think when I felt vacant, and forcing me to write when I felt mute. To Julianne and Baha: thank you for your unwavering friendship, for talking me off metaphorical ledges, and making fun of me when I needed to laugh. Thank you to my friend and editor Laura, who saved me when I was too stubborn to ask for help; to Bea and John for babysitting on the days work beckoned and I had no choice but to answer; and to my sister, Rachel, for offering your time and energy before I even had the chance to ask.

Thank you to my parents, Michael and Natalie Raven. You let us live with you, borrowing your space and your time, and never asked for anything in return. You babysat, did laundry, cooked, cleaned, and entertained. Both of you are wonderful and I couldn't ask for two more supportive or loving parents. To my daughter, Laura: you took your first steps as I wrote these acknowledgements, reminding me that there are much more important things in life than dissertations, and you top the list. Lastly, thank you to my wife, Elizabeth. Thank you for knowing what I wanted to do even when I didn't and believing in me when I couldn't.

I cannot say for certain whether I would have reached this point in my life without you, but I do know that the journey would have been far less enjoyable.

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CHAPTER 1

INTRODUCTION

The terms cognition and metacognition are common in education scholarship, yet still seem to evade concrete description or universal definition (Veenman, 2012). Educators often find themselves using words that are less specific and applying them as synonyms. Cognition becomes synonymous with knowledge; metacognition becomes reflection. These oversimplifications muddle the fields of cognition and metacognition, creating a “fuzziness” in the scholarship rife with misunderstanding (Zohar & Dori, 2012). This lack of universality creates multiple problems. First, researchers are flying blind, in effect. Studying a topic that is both misunderstood and mischaracterized creates a spectrum of contradictory literature. Some authors may characterize metacognition as a set of study strategies (Joseph, 2010), while others characterize those strategies as cognition (Gregory Schraw, Crippen, & Hartley, 2006). One study categorizes critical thinking skills as cognitive (Gregory Schraw et al., 2006), while another considers these skills metacognitive (Kuhn & Dean Jr., 2004). Despite the fact that we are all studying cognition and metacognition, defining them in different ways exacerbates the problem, contributing to the confusion. Second, the lack of universality creates a roundabout in the literature. Educators cannot develop cognition and metacognition in students without understanding them in the first place. We create separate models of *almost* identical concepts, for example, metacognition (Flavell, 1976), meta-knowing (Kuhn, 1999), or self-management of thinking (Jacobs & Paris, 1987). At the same time, we try to clear up this confusion, dedicating entire articles to definitions of metacognition alone (Zohar, 2012), yet rarely offering solutions to the problem of practical application.

To address issues described above, I examined curricular modules that feature 3-D computer environments of biological processes (hereafter these modules will be referred to as simply “modules”) in the secondary biology classroom. They were developed in recognition of the instructional power of highly detailed and accurate animations of anatomical and physiological structures/processes (Sanger, Brecheisen, & Hynek, 2001). The creators of the modules used in this study hypothesized that the use of animations developed to introduce fundamental concepts of biology to high school learners might make an impact on how students learn osmosis, diffusion, and filtration. Thus, the modules were aimed at taking students into an invisible part of the body and then allowing them to test variables and administer treatments to improve the health of that animal or human.

In this dissertation, I examined these modules in conjunction with cognition and metacognition. The study is divided into three separate sections. First, I examined how the modules reflected the students’ knowledge and conceptual understandings of osmosis, diffusion, and filtration. Second, I examined how the students’ knowledge of three concepts common to all of the modules could be characterized over several different learning contexts. Third, using think-aloud interviews that students participated in during their use of the modules, I developed a model to code the resulting data and characterize students’ cognitive and metacognitive knowledge and processes. In this chapter, I present a rationale and purpose for the study as a whole, my research questions, an abstract for each of the three articles that make up the dissertation, and an outline for the rest of the manuscript.

Rationale

This research provided a unique opportunity to study the intersection of cognition, metacognition, and technology in the science classroom. Examining the literature shows gaps in the scholarship on cognition and metacognition (Zohar, 2012), particularly in understanding how science learning through technology might provide a unique window into the study of students' cognition and metacognition. There has been a great deal of research on the use of technology in science classrooms, but the modules that were the focus of this study are remarkably different from many of the technologies currently in use. This research provided a vehicle to test their efficacy as tools for science learning. Additionally, given the limited class time available to accomplish the learning associated with the ever-increasing list of subject matter content standards, it is necessary that research studies explore how educators can best utilize the recent advent of various technologies designed for student learners in science. My examination sought to answer whether these modules could be useful supplements to the science classroom. Additionally, I wanted to facilitate improvement of future students' learning opportunities with regard to fundamental biological concepts. By combining the study of cognition, metacognition, and the specific instructional technology described herein, this dissertation sought to examine not only whether these modules helped to aid student learning, but whether they might help other scholars understand *how* students learn.

Purpose

Cognition and metacognition in secondary students have been recognized as important areas of scholarship within science education for many years. Likewise, the use of computer technology in the science classroom has been growing as a field of scholarship since the 1980s. The modules used in this dissertation work differently than most other technological tools at science teachers' disposal. Developed over the last five years, these cutting-edge modules are computer-learning programs geared toward high school science students. They are one of the few, or perhaps the only, programs that focus on the basic biological and chemical processes of osmosis, diffusion, and filtration—topics covered in the Georgia Performance Standards, the National Science Standards, and the Georgia High School End-of-Course and Graduation Tests. Research is needed to evaluate these modules and determine their usefulness in the secondary science classroom. Likewise, more scholarship must be devoted to the study of cognition and metacognition. As discussed earlier, these concepts are blurred, and in desperate need of clarification. Metacognition in particular is commonly mischaracterized, creating a need for studies that focus on metacognition in the classroom and provide realistic examples of how student metacognition can be characterized.

Research Questions

To gain a better understanding of metacognition, I designed a study to characterize the metacognitive knowledge and processes of secondary science students. However, as metacognition acts on cognition as a second-order process, I first characterized their cognition. I studied students' cognition and metacognition in the context of modules developed around three specific concepts: osmosis, diffusion, and filtration. The research questions framing this study are:

1. In what ways are the students' conceptions of osmosis, diffusion, and filtration represented by their responses to questions both embedded within and external to the modules?

2. How can students' knowledge of molecule movement, concentration gradients, and equilibrium be characterized in different learning contexts, including computer-based modules containing simulations?
3. To what degree can a synthesis of existing scholarship be used to construct a valid model to direct the coding/analysis of student data resulting from interviews related to metacognition while those students are participating in a science learning task?
4. To what degree can analysis of student metacognition using the model described above result in thorough characterization of student metacognition?

Article Overviews

Article #1. In the past two decades, U.S. science education has undergone a massive technological shift (Collins & Halverson, 2010). Technology has been shown to increase student understanding of concepts and support scientific exploration (Wu & Huang, 2007). The computer modules discussed in this study are also considered educational games, which can provide a more interesting and engaging learning environment for students (Sung & Hwang, 2013). In fact, educational video games "promote active learning, critical thinking skills, knowledge construction, collaboration, and effective use and access of electronic forms of information" (Watson, Mong, & Harris, 2011, p. 466). In this study, I examine the implementation and use of three computer modules designed as part of an NIH Science Education Partnership Award (SEPA) grant R43MH096675. These modules focus on the fundamental biological processes of osmosis, diffusion, and filtration, and assess students as they progress through them using both forced-choice and open-ended questions.

Out of a pool of six hundred students, six students were selected for an in-depth quantitative assessment. Pre, post, and post-post test scores were considered, as well as scores from the embedded questions in the modules, which were graded with rubrics that were continually developed throughout the duration of the study. Using descriptive statistics, rubrics, and chi-squared analyses, I evaluated the students' scores over the course of the unit. The results showed that although students displayed some concrete understandings of osmosis, diffusion, and filtration, the modules made little difference in affecting their understanding. Breaking down student understanding by concept showed similar trends. Additionally, the students had a higher percentage of correct scores on forced-choice questions than on open-ended questions, implying that their knowledge of the concepts of osmosis, diffusion, and filtration may not have been as complete as their performance on the forced-choice questions suggested. Although it is still unclear whether the modules made any significant impact in terms of student understanding, it is evident that more research is necessary in order to investigate students' conceptions of these scientific concepts, as well as the usefulness of the modules.

Article #2. In education, the need to understand how students learn—specifically, how much and which types of knowledge are acquired—is imperative to both classroom management and educator research. While there is much in the way of scholarship devoted to students' knowledge of various topics in science, this research is usually limited to memory of individual, specific concepts or snapshots of student understanding (i.e. Friedler, Amir, & Tamir, 1987; Odom & Barrow, 1994). In an effort to provide a different perspective, I chose in this study to evaluate student knowledge of three related and important scientific concepts through different methods of assessment. Additionally, I chose to frame this study around the use of curricular modules that feature 3-D computer environments of biological processes, as computer animations and video games have been shown to aid student learning (De Jong & Van Joolingen,

1998) and promote a wide variety of skills, including higher-order thinking, teamwork, and conceptual understanding (Watson et al., 2011).

In an attempt to characterize students' knowledge within a variety of learning contexts, I focused on the experiences and evaluations of three case studies as they completed the modules, which serve as both an evaluation tool and a teaching tool. In this study, I sought to address the following question: How can students' knowledge of molecule movement, concentration gradients, and equilibrium be characterized in different learning contexts, including computer-based modules containing simulations? I was particularly interested in student learning and how to characterize student knowledge. In evaluating the results I also considered the pre, post, and post-post tests, the post-interview, and the post-post free response survey. Using these sources of data, as well as drawings created by the students during the post-interview and the post-post survey, I created a characterization of student knowledge at different stages and through different evaluations. I qualitatively analyzed the work of three participants, coding the data for their understanding of the scientific concepts they were expected to glean from the modules, while also noting additional trends.

Results from my analysis showed that, despite fairly consistent test scores and forced-choice question scores within the modules, the students maintained misconceptions related to molecule movement, concentration gradients, and equilibrium throughout the unit. These misconceptions not only affect students' learning of these concepts, but their future understanding of other key concepts, including chemical equilibrium, respiration, photosynthesis, and many other biological and chemical processes. However, regardless of the effect the modules had on student understanding, it is clear that using contextual knowledge characterization as an analytic tool can provide deeper understanding of student knowledge and cognition.

Article #3. Teachers are charged with educating students and providing them with meaningful learning experiences, but what learning is considered meaningful, and on what basis can it be decided that students are sufficiently educated? Many researchers believe that, instead of relying on standardized testing, teachers focusing on better education help students to surpass surface understanding and dig deeper into their own learning processes (Garofalo & Lester Jr., 1985; Pintrich, 2002). Although there is a great deal of disagreement on how we can best increase student accomplishment of this deeper understanding, it is generally agreed upon that studying students' metacognition—thinking about thinking—will lead us in the right direction (Georghiades, 2000). Unfortunately, how best to develop students' metacognitive knowledge and skills, how to evaluate metacognition, and even the definition of metacognition are topics of debate among education scholars (Zohar & Dori, 2012). Through investigating students' reactions to and benefits from three computer-based modules covering important and often misunderstood science concepts (osmosis, filtration, and diffusion), I worked toward a better understanding of these problems of metacognition within a science education context. In my research, high school students engaged in curricular modules featuring computer animations of biological processes (hereafter referred to simply as the modules). I engaged in "think-aloud" interviews with the participants as they completed each module, recording their thought processes and self-knowledge of learning strategies.

In my attempt to deepen the pedagogical understanding of metacognition and resolve the issues that arise from its complicated nature, I sought to answer the following research questions:

1. To what degree can a synthesis of existing scholarship be used to construct a valid model to direct the coding/analysis of student data resulting from interviews related to metacognition while those students are participating in a science learning task?
2. To what degree can analysis of student metacognition using the model described above result in thorough characterization of student metacognition?

To answer these questions, I first engaged in a meta-analysis of the literature on metacognition. Using various components from previously developed models, while also drawing on my own experiences, research, and conceptions, I created a model to code think-aloud interview data for students' cognitive and metacognitive knowledge and processes. The results of this analysis showed that the model could be applied in individual assessments to determine and solve student-learning issues, or on a broad classroom scale to evaluate instructional effectiveness in training metacognition and cognitive skills. Overall, the model I have proposed fills an absence in the literature that is necessary for clearing up some of the ambiguity that surrounds metacognition, as well as adding to the limited literature on methodologies of analyzing data for metacognition. Through its implementation, educators will be able to categorize students' knowledge and thought processes during learning (as opposed to post-learning evaluations), make extensive use of the concurrent think-aloud protocol by effectively coding the data, and present deeper analyses of cognition and metacognition.

CHAPTER 2

SECONDARY SCIENCE STUDENTS' CONCEPTIONS OF OSMOSIS, DIFFUSION, AND FILTRATION: KNOWLEDGE GROWTH MEDIATED BY CURRICULAR MODULES THAT FEATURE 3-D COMPUTER ENVIRONMENTS OF BIOLOGICAL PROCESSES

Digital technology has become a fact of life in all aspects of our daily world; its impact in education is causing a shift in how teachers teach and how students learn. Where once blackboards and chalk commanded the front of classrooms, we now find SMART Boards and digital markers. GoogleDocs and DropBox have all but replaced hanging files and folders, and where teachers used to rely on transparencies, we now have PowerPoint and Prezi. Although anecdotal, these examples represent the reality of schooling today: "The world of education is currently undergoing a second revolution. Digital technologies such as computers, mobile devices, digital media creation and distribution tools, video games and social networking sites are transforming how we think about schooling and learning" (Collins & Halverson, 2010, p. 18). Not only have educational tools become increasingly technological, research programs have also grown from this development, aimed at increasing the use of these technologies (Varma, Husic, & Linn, 2008). This increase in technology has led science education scholars to attempt to integrate technology into their practices and advocate for the continued use of it in the science classroom due to its potential to support science-specific instruction through inquiry, hands-on participation, activities, and lab work (Wu & Huang, 2007).

In this study, I examine students' use of curricular modules that feature 3-D computer environments of biological processes. The modules were created with the intended purpose of helping students explore scientific ideas through the use of realistic computer simulations and video game–style exploration. Funded by an NIH SEPA grant, the founding researchers of this project created the modules with the understanding that “educational computer games could be an effective way of providing a more interesting learning environment for acquiring knowledge” (Sung & Hwang, 2013, p. 43). Three modules were created, covering the topics of osmosis, diffusion, and filtration, and are the subject of a larger NIH-SEPA grant-funded study with over 500 high school biology students. Although data from a large population can have very powerful and far-reaching implications, a limited pool of subjects leads to more thorough and deeper analysis. As an accompaniment to the larger study, therefore, I chose a small subset of data from six students to analyze in order to test the modules’ usefulness in the classroom and determine how the tests and modules capture students’ knowledge of osmosis, diffusion, and filtration.

Research Questions

In this quantitative study, I was specifically interested in students’ knowledge of osmosis, diffusion, and filtration in relation to the modules. The reasons for this were twofold. First, the underlying premise of these modules’ creation was that, as a technological tool, they would increase student understanding of osmosis, diffusion, and filtration. I aimed to evaluate that understanding and determine whether this increase existed. Second, the use of educational games to help stimulate learning is well documented (Ellis, Heppel, Kirriemuir, Krotoski, & McFarlane, 2006). In fact, it has been shown that “video games promote active learning, critical thinking skills, knowledge construction, collaboration, and effective use and access of electronic forms of information” (Watson et al., 2011, p. 466). Therefore, through this study I aimed to both evaluate student learning, and examine the role that the game-style modules played in this learning. The following research question guided this study: In what ways are the students’ conceptions of osmosis, diffusion, and filtration represented by their responses to questions both embedded within and external to the modules?

Review of the Literature

Before delineating the results of this study, I have provided a theoretical context explaining both the content and the logic behind each module. I began by providing a brief overview of the modules used in this study. Next, I situated the modules as computer simulations and educational games, describing the different types of computer simulations and their usefulness in science classrooms. As the purpose of the modules is to build students' knowledge of specific science topics, I also devoted a portion of this review to student learning and knowledge of science concepts. Lastly, to familiarize readers with the science concepts in this study (osmosis, diffusion, and filtration), I provided an overview of the science topics students are expected to learn from the modules.

The Modules. The three modules in this study were created to "address the lack of student engagement in high school science classrooms" by "embedding information about biological processes, such as osmosis, diffusion and filtration, into intriguing case studies that engage students, while adding a gaming element" (IS3D, 2012). The first case centers on osmosis, the second, diffusion, and the third, filtration. In addition to deepening student knowledge on these topics specifically, in a broader sense the modules stimulate students' higher order learning processes through free-response questions that involve greater depth of thinking and knowledge than is typically needed for forced-choice questions, for example multiple choice or true-or-false. In the osmosis case, students take on the role of a veterinarian helping to treat a calf with cerebral edema. Instead of explaining the concept on a strictly cellular level, this exercise asks students to consider the effects and applications of osmosis. In the module, Clark the calf has ingested too much water and, as a side effect, his blood sodium level has lowered. The students are provided with three IV saline solutions as treatment options: a hypertonic solution, a hypotonic solution, and an isotonic solution. Choosing what they think will work best to alleviate Clark's symptoms and lower his blood sodium level, the students work through Clark's treatment, taking various measurements within Clark's brain to assess his progress. Throughout this module, students are presented with information about osmosis, concentration gradients, and equilibrium with the digital manual, with illustrations and text, similar to an interactive textbook.

In the diffusion case, students are charged with helping a victim of a train crash. Based on a true event involving a train collision in a small town that released toxic chlorine gas into the air, this module helps students learn about three concepts that are related to concentration gradients of lung gasses—concentration difference, diffusion distance, and alveolar surface area. Using this knowledge, they provide treatment to the patient in the form of oxygen, diuretics, and corticosteroids. Lastly, in the filtration case, students take the role of a doctor's assistant, helping a patient undergo dialysis treatment. During this case, students take an in-depth look at the process of dialysis and filtration, building on their knowledge of concentration gradients by learning about parallel versus countercurrent flow. In this module, students travel into a dialysis machine, changing the pore size of the filter and the direction of flow to increase the effectiveness of the patient's dialysis.

Educational Technology in the Science Classroom. The modules described above are representative of a growing trend in science education toward electronic teaching tools. In this study, I focus on the implementation of computer simulations designed to help students understand scientific concepts. Computer simulations are defined as "a program that contains a model of a system (natural or artificial; e.g., equipment) or a process" (De Jong & Van Joolingen, 1998, p. 180). There are two types of computer simulations: those that illustrate concepts and those that illustrate operations. As De Jong and Van Joolingen explain, "Conceptual models hold principles, concepts, and facts related to the (class of) system(s) being simulated." Operational models, on the other hand, "include sequences of cognitive and noncognitive operations (procedures) that can be applied to the (class of) simulated system(s)" (p. 180). The modules used in this study are conceptual; they provide students an opportunity to explore the scientific processes of osmosis, diffusion and filtration using simulated experiences. Using the modules, students are able to visualize aspects of biology at the cellular level, potentially increasing their understandings of the concepts. Furthermore, these experiences were also designed as inquiry activities, which served the dual purpose of allowing students to guide their own learning through trial-and-error and open-ended experimentation, as well as move at their own pace in order to maximize their learning.

Technology is quickly becoming a fundamental component of science classrooms in the United States. Despite this development, though many teachers attempt to integrate technology into their lessons in modern ways, "they remain the exception rather than the rule" (Means, 2010, p. 285). The modules are tools designed as an entire unit to promote student learning and increase interest in science. This is especially important, as the evolution of the profession has resulted in a so-called learning curve for teachers:

> Most educators will expend the effort needed to integrate technology into instruction when, and only when, they are convinced that there will be significant payoffs in terms of student learning outcomes. Hence, to make technology an agent of education change, the field needs to understand the kinds of learning outcomes that technology can enhance and

> the circumstances under which that enhancement will be realized in practice. Sound guidance on how to implement technology in ways that produce student learning gains is integral to efforts to use technology as a lever for education change. (p. 287)

The modules fill these needs: science teachers would be able to evaluate student learning easily using the embedded questions in the modules. They could simultaneously enhance learning by providing visualizations of cellular-level processes, which may make learning both easier and more entertaining. Computer programs that provide visualizations are especially useful: "visualization aids student understanding of complex processes because it assists in the conversion of an abstract concept into a specific visual object that can be mentally manipulated" (McClean et al., 2005, p. 170). As all of the processes in the modules take place at the cellular level—too small to see without the aid of very powerful and expensive technologies (i.e. electron microscopes)—this advantage becomes exceedingly important. Providing visuals of these processes can assist students in gaining a more complete understanding of the process and interactions, as opposed to just the language and the results. Additionally, research has shown that "by using well-designed visual tools, students can digest large amounts of information in a relatively short time and construct their own personal visualization of a process" (McClean et al., 2005, p. 170). Potentially, a module in this vein could increase teacher efficiency by removing time spent lecturing (thus freeing up more time for individual engagement) and increasing the amount of information that students' can process in a fixed period. Others argue that "These animations have the potential to make it easier for students to understand difficult science concepts," (Thatcher, 2006, p. 9) meaning that students may not only learn faster, they may be able to grasp concepts with less stress or frustration. In each of the modules, students are expected to explain their choices and rationalize their "treatments." Additionally, each of the modules is constructed to relay a story and progress through a narrative. This is important, as research indicates that "animations and graphics with a spoken or written narrative are more effective than those lacking a narrative" (O'Day, 2007, pp. 217–218). For instance, the majority of the students who finish the osmosis module have told me that, although they learned a great deal from the module, they were excited that they had saved Clark the calf. Working through the module with this narrative provided students with an opportunity to form an emotional connection to the main character, immersing them more deeply in the storyline and the module than if Clark had not been the subject of the module. Through the use of stories, detailed computer graphics, and gameplay style learning, students are not only able to engage in a self-directed science lesson, but gain valuable knowledge through entertainment.

Students' Science Knowledge. Although the scholarship devoted to student cognition is expansive, literature on student knowledge of specific science topics is limited (Koedinger, Corbett, & Perfetti, 2010). Most of the research on student learning in science has to do with either assessment, (e.g., O'Reilly & McNamara, 2007) or students *views* of scientific knowledge, rather than their knowledge of specific science topics (e.g., Hogan, 2000; Songer & Linn, 1991). This kind of evaluation is less quantitative in nature. In cases when researchers have focused on knowledge of specific science topics, evolution is by far the most popular topic for consideration (e.g., Anderson, 2007), rather than knowledge of other, less politically charged, science concepts, such as osmosis. The concept of evolution is a unifying topic in science that is "central in the organization and principles of science" (Lee & Liu, 2009, p. 666). I argue, however, that osmosis, diffusion, and filtration are also essential concepts in science. These concepts are found in both state and national secondary science standards in biology and chemistry (Board on Science Education, 1996; Georgia Department of Education, 2011), and play an essential role in the Next Generation Science Standards (Achieve Inc., 2013). Additionally, the relationship between osmosis, diffusion, and filtration is explored throughout most high school science courses, as well as many postsecondary biological sciences.

Scholarship on the use of curricular supplements, such as educational video games, points toward conclusive findings about student understanding of particular topics. In the coming section, I consider some of the findings about student understanding of osmosis, diffusion, and filtration. One study found that "students find [osmosis and diffusion] very difficult to understand and several biology education researchers have reported student misconceptions associated with these topics" (Sanger et al., 2001, p. 104). Odom and Barrow (1994) too found that:

> Construction of scientifically acceptable understanding of diffusion and osmosis conceptions did not occur for the large majority of secondary biology students in the study. Strong misconceptions were detected about concentration and tonicity, influence of life forces on diffusion (and osmosis), membranes, particulate and random nature of matter, the process of diffusion, and the process of osmosis. With the exceptions of the kinetic energy of matter and one item on the particulate and random nature of matter, guessing occurred more often than the desired content knowledge. (p. 99)

These results are not singular; others have reported data that echoes these misconceptions. In a project that investigated the conceptions of osmosis held by nearly 500 secondary science students, five main misconceptions were highlighted:

> (1) The most frequent explanation offered to osmosis is "a desire or drive towards equalizing concentrations." (2) Hardly any student uses the concept "water concentration." (3) Most students fail to realize that in dynamic equilibrium water

> molecules keep moving. (4) Students have special difficulty in understanding osmotic relations in plants. (5) Many students have difficulty in grasping solute-solvent and concentration-quantity relations. (Friedler et al., 1987, p. 541)

Although students characterized osmosis as "a desire or drive towards equalizing concentrations," they did not use the concept of water concentration in their explanations during interviews, meaning that they were most likely repeating a phrase instead of creating their own explanation. Additionally, the third and fifth misconceptions show that students do not understand that solute-solvent concentration is the impetus for osmosis, or that an equal concentration does not mean that molecules stop moving. In one of the only studies aimed at computer animations and their impact on students' understanding of osmosis and diffusion, Sanger, Brecheisen, and Hynek (2001) found that

> …students who viewed computer animations depicting the molecular processes occurring when perfume particles diffuse in air and when water osmoses through a semi-permeable membrane developed more accurate conceptions of these processes based on the particulate nature and random motion of matter. (p. 108)

This would indicate that visualization played a key role in the learning/teaching process. This article is over a decade old, however, and the computer animations utilized in the study are outdated. The visualizations that the program provided were basic, one-dimensional representations of molecules and did not provide a context for the processes occurring. The modules used in my study provide students with a much more detailed and accurate picture of osmosis and immerse them in realistic contextualized environments. Examining whether modules like these can impact students' understanding of osmosis, diffusion, and filtration fills a void in the scholarship on a topic that is essential in the secondary science classroom.

Osmosis, Diffusion, and Filtration. What follows is an explanation of the conceptual and factual subject matter on the topics of osmosis, diffusion, and filtration in terms of their representation in the modules. Osmosis is the movement of solvent (in this case, water) molecules across a selectively permeable membrane. This movement is driven by a concentration gradient, wherein free water moves from an area of high concentration to an area of low concentration. Commonly misunderstood, this movement occurs because of solute concentration (i.e. the amount of particles in a given space), and although water moves from high to low areas of concentration *of water molecules*, it moves from areas of low to high concentration *of solvent molecules*. Once equilibrium has been reached, the net flow of water molecules ceases, however, water molecules still continue to travel through the membrane equally from either side. A key aspect of this process covered in the modules but not usually in high school biology classes is that of free water. Free water molecules are water molecules not bound to solutes dissolved in a solution. Different concentrations of solute molecules mean different concentrations of free water molecules. These differences are because in areas of high solute concentration, more free water binds with the solute molecules, causing a decrease in free water. Therefore, during osmosis, water molecules actually move from an area of high *free water* concentration, to an area of lower *free water* concentration. This is important, as bringing in the concept of free water helps students make sense of osmosis and the importance of solute concentration.

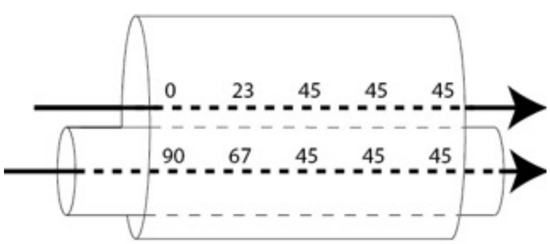
In addition to introducing free water molecules, the osmosis module requires students to apply this new information to understanding hypertonic, hypotonic, and isotonic solutions. Isotonic means that two solutions being compared have an equal concentration of solutes. A hypertonic solution has, in comparison to another solution, a higher concentration of solutes.

Hypotonic means that the solution has, in comparison to another solution, a lower concentration of solutes. In terms of the module, these different solutions are used as potential treatments to the problem that Clark the calf is experiencing. In the module, Clark has been experiencing diarrhea, so his owners gave him excess amounts of water. This dangerously lowers Clark's blood sodium levels, causing water to flow from the area with a higher concentration of water (the blood vessels) and into the area with a lower concentration of water (the brain matrix). The increase in pressure caused by the increased movement of water into his brain matrix causes increased firing rate of neurons and ultimately, causing Clark's seizures. In order to appropriately treat Clark, the student must choose to administer a hypertonic solution, increasing his blood sodium levels. As the solute concentration in his blood increases due to the administration of the hypertonic solution, water travels from the area with the now higher concentration of free water molecules (the brain matrix) to the area with the now lower concentration of free water molecules (back into his blood), thereby decreasing the pressure in his brain and stopping the seizures. The most important science concept in this module is that the process of osmosis is driven by differing solute concentrations on either side of a selectively permeable membrane, and that water moves from an area of high water concentration to an area of low water concentration.

The diffusion module builds on some of the concepts learned in the osmosis module. Diffusion is the movement of molecules from a high concentration to a low concentration, which occurs as a result of the collision between molecules as they randomly move. As the molecules collide into one another, they begin to spread out, becoming less clustered and more evenly spaced through random movement. This molecular movement occurs both within confined areas and across selectively permeable membranes. In the diffusion module, this movement occurs across a selectively permeable membrane separating alveoli from the blood. Students learn about three factors that affect the rate of diffusion: concentration difference, diffusion distance, and surface area. Concentration difference refers to the difference in molecules on either side of a membrane. The greater the concentration difference, the faster diffusion occurs. This is due to the increased collision of particles since there is less area for the particles to move around without colliding. Diffusion distance is the distance a molecule must travel to diffuse from one side of a membrane to the other side. The shorter the distance, the faster diffusion occurs. Surface area refers to the total space the molecules occupy. The larger the surface area, the quicker diffusion will occur. In the module, all of these factors are in reference to the alveoli of a patient's lung. After the patient inhaled toxic chlorine gas due to a rupture of a canister on the wrecked train, her alveoli became inflamed. This increased the diffusion distance of the respiratory membrane due to the swelling of membranes, caused a build-up of fluid, (decreasing the surface area), and decreased her blood oxygen levels (lessening the concentration difference). She is diagnosed with hypoxemia, the condition of having less oxygen in the blood. In order to treat her, students are given three treatment options: oxygen delivered via nasal prongs, diuretic delivered by injection, and corticosteroids delivered by nebulizer.

Although all of the treatments must be administered to complete the module, the students are allowed to determine the order in which they are given based on how quickly each treatment works, and its side effects. The oxygen takes effect immediately, increasing the amount of oxygen in her blood. This increases the concentration difference between her blood and alveoli, and as a result, oxygen diffuses into her alveoli. The diuretic takes about an hour to take effect and removes excess fluid by increasing the excretion of fluid from the body. The decrease of fluid increases the surface area, increasing the rate of diffusion of oxygen into the alveoli. Lastly, the corticosteroid, which takes several hours, is used to reduce swelling and lessen inflammation of tissues. In this case, the corticosteroid decreases the diffusion distance by reducing the swelling of the alveolar membrane. Although the treatments can technically be given in any order, the developers of the modules intended for students to choose to administer the treatment based on how quickly the treatments works, with the most immediate effect (oxygen) first, and the treatment with the slowest effect (corticosteroid) last. The most important science concept in this module is that diffusion is affected by a variety of factors, including concentration difference, diffusion distance, and surface area.

Building mainly on the osmosis module, the filtration module covers the concept of dialysis, which is the process of filtering blood through a dialysis machine. Dialysis is commonly used to maintain the health of people with diabetes by removing excess water, solutes (such as potassium), and waste products (such as urea). During this process, proteins, such as albumin, should not be removed. In order to accomplish the potassium and urea removal, a dialysis machine uses a filter (a selectively permeable membrane) with pores big enough to allow certain molecules through, such as potassium and urea, while blocking the movement of bigger molecules, such as albumin. Dialysis uses the process of diffusion to filter the blood by pumping it through one side of a selectively permeable membrane. Dialysate, which is a special dialysis fluid, is pumped through the other side of the membrane. Since there is more potassium and urea in the blood than in the dialysate, those molecules filter into the dialysate, removing them from the blood. However, since the pores of the filter are too small for the albumin to fit through, it does not get removed from the blood, despite there being more albumin in the blood than in the dialysate. Additionally, as the potassium and urea are removed, free water flows from an area of high concentration (the blood, which was an area of low concentration) to an area of lower concentration (the dialysate), removing excess water and lowering the patient’s mass. The blood and dialysate can run either parallel to each other (parallel flow) or counter to each other (countercurrent flow). In parallel flow, the blood and the dialysate separated by the selectively permeable membrane (in this case, the dialysis filter) flow in the same direction. In countercurrent flow, the fluids run in opposite directions. Figure 2.1 shows both types of flow and illustrates the concentration of molecules on either side of the selectively permeable membrane. The top arrow in each illustration represents the concentration of urea in the dialysate, and the bottom arrow represents the concentration of urea in the blood. As can be seen in the top picture, the dialysate has no urea at the left side of the filter. As the two fluids are pumped through the filter, urea begins to flow from the area of high to low concentration, or from the blood into the dialysate. However, equilibrium occurs as the two fluids reach the same amount of urea, stopping the flow of urea out of the blood. Countercurrent is much more efficient than parallel flow because, as the molecules move from an area of high to low concentration, an equilibrium is never reached, therefore never stopping the flow of urea from the blood into the dialysate. In this module, the most important science concept that students learn is the process of dialysis and how the process can be made more effective through the alteration of the size of the pores in the filter and the direction of fluid flow.



Parallel Flow

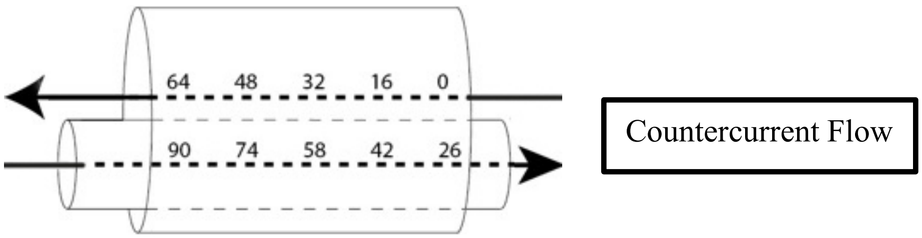


Figure 2.1. Parallel versus Countercurrent Flow: Concentration (µL/g) of Urea.

Methods

This section details my participant selection process, data collection methods, and the methods I used to analyze the data.

Participant Selection. This quantitative study was one of three studies that I designed around the modules. As the other two studies were qualitative, I decided to use a small, but diverse, sample population, rather than a larger number of participants. Additionally, the larger study associated with this dissertation began with 506 ninth-grade biology students in gifted, honors, and college-preparatory (CP) classes, and their six biology teachers. Given the number of participants, I needed a multi-tiered selection process to scale down the number of participants to a much more manageable size. I began my selection by first asking each of the teachers for the names of between two and four students who would most likely be forthcoming about their thought processes. Because the participants would be engaging in think-aloud interviews with me, it was vital that they be able to discuss their thought processes. After receiving the names, I had 49 potential participants. In order to narrow down my selection, on day one of the study, I administered and scored two tests: the content pre-test and the Metacognitive Awareness Inventory (MAI) (Gregory Schraw & Dennison, 1994). The content pre-test, a multiple-choice assessment of students' knowledge of osmosis, diffusion, and filtration, and the MAI, a true/false assessment of students' metacognitive knowledge and strategies, will be described in detail in the next section. I averaged the scores for each of these tests for the CP classes and the Honors/Gifted classes. Using these averages as a base, I created a quadrant between MAI and Content scores, which is shown in Figure 2.2. I then sorted students into these following four quadrants based on their individual scores.

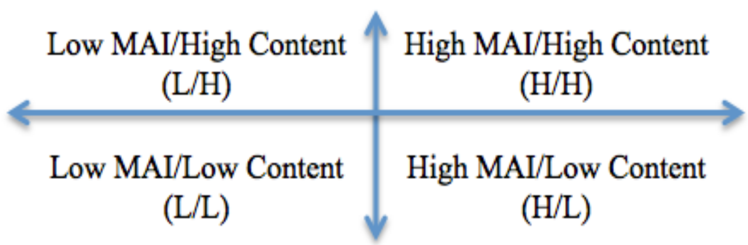


Figure 2.2. Score Quadrants for Participant Selection.

For instance, if a student scored less than average on the MAI and higher than the average on the content pre-test, I sorted them into the Low MAI/High Content (L/H) quadrant. I should note that I did not use the content pre-test or the MAI to remove any potential participants. Rather, I used them to establish a profile for each participant, sorting everyone into score quadrants in order to choose the most diverse population of participants as possible. Using a random number generator, I then picked one student from each class period and class type (honors/gifted versus college-preparatory) for a total of ten participants. I evaluated and re-chose in certain situations to ensure that there was enough variety in gender and score quadrant; I chose to use a criterion-based sampling method in order to gather a richer data set, despite the small number of participants (Merriam, 1988). This meant that I chose students randomly, as long as the number of male and female participants remained equal, and no more than three students were selected from each score quadrant. In several cases, the students I chose did not wish to participate, forcing me to use instrumental selection, which is a selection method that relies on who is available rather than who is chosen, to select other participants with the same characteristics (Stake, 1995). I originally began with the intent of having ten participants from both CP and gifted/honors classes. After more consideration, however, I decided to only include gifted/honors students. Two main factors influenced this choice. First, past research in this project had shown that lower-level students do not understand the concepts from the modules as well as upper-level students. Their answers on the free-response questions tended to be less detailed, and many of them were left blank. Second, once the CP students began using the modules, it quickly became clear that they would not be able to finish the modules in the time allotted, meaning I would end up with incomplete data sets. For both of these reasons, I completed my selection with the participants listed in Table 2.1 (all names are pseudonyms).

Table 2.1
Participant Details

Teacher	Student Name	MAI	MAI %	Content	Content %	Sex	Quadrant
A	Emma	19	70.37%	10	47.62%	F	L/L
B	Kendra	16	59.26%	13	61.90%	F	H/L
B	Henry	15	55.56%	11	52.38%	M	L/L
B	Monica	22	81.48%	18	85.71%	F	H/H
C	Joey	25	92.59%	11	52.38%	M	L/H
D	Riley	21	77.78%	13	61.90%	M	H/H

Data Collection. In order to evaluate my participants' conceptions of osmosis, diffusion, and filtration, I used multiple data sources, both within and external to the modules, including a pre-test, a post-test, a post-post test, and all of the embedded questions, both forced-choice and free-response, in each module. This facilitated a more accurate exploration of data, as the use of multiple sources of data supports triangulation and validity (DeMarrais & Lapan, 2004). The sources of data that I used, as well as the timeline of data collection, are listed in Table 2.2.

Table 2.2
Data Collection Methods and Timeline

Data Collection Method		**Data Collection Timeline**					
		Oct. 9th, 2012	Oct. 22nd to Oct. 26th, 2012			Oct. 29th to Nov. 2nd, 2012	Dec. 12th, 2012
Pre-test		X					
Metacognitive Awareness Inventory		X					
Embedded Free Response Text Questions	Osmosis		X				
	Diffusion			X			
	Filtration				X		
Post-test						X	
Post-post-test							X

The research team associated with the larger study designed and validated the pre, post, and post-post tests used to assess participant subject matter knowledge of osmosis, diffusion, and filtration. The pre-test contains 21 multiple-choice items designed as a formative assessment of students' knowledge prior to their study of the cell unit, (the unit of which the modules were a part). The post and post-post tests contain 29 multiple-choice items. The extra eight items are ~~anchor~~ questions designed to test students' knowledge of module-specific content. There were two forms of the tests used: A and B. Most of the questions are identical, and the questions that are differently worded test students for the same content. For instance, question one on form A is:

1. The movement of water molecules across a selectively permeable membrane is called ___________.

    a. diffusion

b. filtration

c. homeostasis

d. osmosis

Question one on form B is:

1. Osmosis is defined as the diffusion of______________________.

a. water movement from a hypertonic to a hypotonic region

b. water through a selectively permeable membrane

c. a solute through a selectively permeable membrane

d. sodium chloride from a higher to lower concentration

Both questions test students' knowledge of the definition of osmosis, but they are worded differently. Students alternated between test forms for each testing day, so those who took form A for the pre-test took form B for the post-test, then form A again for the post-post test. The tests were designed in this manner to reduce bias from repeat testing.

The MAI, created by Dennison and Schraw (1994), was designed to "generate and test an easily administered metacognitive inventory suitable for adolescents and adults" (p. 461). A 52-item true/false survey, the instrument tests students on both knowledge of cognition and regulation of cognition. The items that are categorized as relating to the knowledge of cognition are factored into subgroups that assess (a) declarative knowledge (knowledge about one's skills), (b) procedural knowledge (knowledge about implementing learning strategies), and (c) conditional knowledge (knowledge about when and why to use learning strategies). The items that are categorized as regulating knowledge of cognition are factored into subgroups that assess (a) planning (steps taken prior to learning), (b) information management (skills used to process information), (c) monitoring (assessing one's learning), (d) debugging (strategies used to correct errors), and (e) evaluation (analyzing one's own performance).

Because a 52-item survey could not be used for the larger study due to time constraints, I pared down the instrument, keeping 27 total items. In order to identify the items that were the most directly connected to the goals of the study, I applied the following methods and criteria for selection. First, I calculated the percentage of questions that made up each subgroup. Referring to these percentages, I made sure to remove items in a manner that the percentages did not differ greatly from the original make-up of the instrument, save for the planning category. After consideration, I decided that the planning category would not be necessary for assessing participants, since in this study I was not concerned with how students planned on approaching the modules. This decision was made on the basis that the students were unaware of the modules at the start of the unit and, therefore, could not plan an approach to completing them. Second, I removed any items that seemed to assess similar attributes. For example, item 51 ("I stop and go back over new information that is not clear") and item 52 ("I stop and reread when I get confused") are very similar items. In this case, I kept item 52, which I felt was more general, and removed item 51. The final MAI is listed in Appendix A.

As mentioned earlier, each of the modules contained embedded forced-choice and free-response questions. Most of the forced-choice questions provided students with immediate feedback—the module does not allow students to move forward until the question has been answered correctly—though there are exceptions to this. For instance, in the osmosis module, students are asked to choose the most effective and least effective treatment option. This question can be answered incorrectly with the students still able to proceed through the module. The open-ended questions, conversely, do not ever provide feedback. At various points in the modules, students are asked to explain their reasoning. For instance, after choosing a treatment option in the osmosis module, students are required to explain why they chose the treatment. These responses are not graded within the modules, but the forced-choice questions are graded as follows: if the student answers correctly the first time, full points are given. If the student answers incorrectly the first time, no matter how many tries it takes to eventually answer correctly, no points are rewarded. As the modules do not score the free-response questions, scoring rubrics had to be developed. Over the past year, my colleagues and I created and edited rubrics for each module, triangulating the process by making sure that all of those involved in the rubric modification process could grade and agree upon scores. The rubrics for each module are listed in Appendices B (osmosis), C (diffusion), and D (filtration).

Data Analysis. I separated my analysis into two parts: the embedded questions from the modules and the pre, post, and post-post tests. I first scored each test and calculated the difference between the pre, post, and post-post tests for each student. Using descriptive statistics, I quantitatively determined test percentage averages and percent difference averages for various groups, including each test (e.g., average of all students for the pre-test), each student (e.g., average test percentage and test percent difference for Emma), and the MAI/Content pre-test score quadrants into which students were originally sorted (e.g., average test percentage for all students sorted into the low content quadrant). Afterward, I categorized the test questions from the pre, post, and post-post tests into the three content areas: osmosis, diffusion, and filtration. For instance, question 1 on test form A is:

1. The movement of water molecules across a selectively permeable membrane is called ___________.
    a. diffusion

b. filtration

c. homeostasis

d. osmosis

Since this item is used to test students' knowledge of osmosis, I categorized it as an osmosis question. Using this categorization method, I used two separate chi-squared tests to analyze the data. First, I used only the 21 questions common to the pre, post, and post-post tests, in other words, without the anchor questions. This test was used to determine whether there was a significant relationship between the three tests and the category of questions. Additionally, since the anchor questions were only used in the post and post-post test, I categorized those separately and used another chi-squared analysis to determine whether there was a significant relationship between the post/post-post test and the anchor questions.

For the embedded questions, since the program scores the forced-choice items, I began by scoring the free-response items using the previously discussed rubrics. I combined the forced-choice and free-response questions scores to calculate an overall percentage for each student and module, as well as percentages for each section of the modules (broken down below). Lastly, for each module, I counted the number of points from the free-response questions to determine whether a relationship existed between the score percentages and the free-response ratio of points.

Results

Below, I first discuss the test results, focusing on the raw test percentages, the percent differences between tests, and the average test percentages by the MAI/Content score quadrants. I then move on to the results of the embedded question analysis and discuss the average score percentages, as well as the ratio of free-response points and its relationship to the embedded question scores.

Test Scores. The raw test score percentages for each student and test are listed below in Table 2.3. The data clearly shows that the pre-test had the lowest percentage of correct answers and the post-test had the highest percentage of correct answers, showing that at least in the short term, the modules increased student knowledge on the topics. When I calculated the percent differences between the tests for each student (Table 2.4), several interesting themes emerged. For instance, Henry had the most marked increase between the pre and post-test, but also tied for the highest decrease between the post and post-post test, which was proctored over a month after students completed the modules. The students with the lowest percent increase between the pre and post-test (Riley and Monica) also had the lowest percent decrease between the post and post-post test. Breaking down the test score percentages down by MAI/Content quadrant yielded other themes. As seen in Table 2.5, those students sorted into the low MAI quadrants initially had a higher overall average percentage across the pre, post, and post-post tests. The students initially sorted into the high content score quadrants also had higher overall average percentages across the pre, post, and post-post tests. Table 2.6 shows the differences between the test score percentages broken down by quadrants. Interestingly, the greatest average change in score between the pre and post-test, and the pre and post-post test, came from averaging those placed in the high MAI score quadrants (quadrants H/H and H/L), as well as averaging those placed in the low content score quadrants (quadrants H/L and L/L). Table 2.7 shows the results of the chi-squared analysis for the test questions separated by topic. The test showed no discernable relationship between the three tests and the category of questions missed ($\chi^2 = 0.311$). Table 2.8

shows the results of the chi-squared analysis for the anchor test questions separated by topic. A chi-squared analysis of the anchor questions also showed no relationship ($\chi^2 = 0.931$).

Table 2.3
Students' Raw Test Score Percentages

Student	Pre	Post	Post-Post	Average	Quadrant
Emma	47.62%	72.41%	68.97%	63.00%	LL
Riley	61.90%	68.97%	65.52%	65.46%	HH
Joey	52.38%	82.76%	72.41%	69.18%	HH
Kendra	61.90%	86.21%	65.52%	71.21%	LL
Henry	52.38%	93.10%	72.41%	72.63%	HL
Monica	85.71%	93.10%	89.66%	89.49%	LH
Average	60.32%	82.76%	72.41%		

Table 2.4
Differences between Pre, Post, and Post-Post Test Score Percentages by Student

Student	Pre/Post Difference	Post/Post-Post Difference	Pre/Post-Post Difference
Emma	24.79%	-3.45%	21.35%
Riley	7.06%	-3.45%	3.61%
Joey	30.38%	-10.34%	20.03%
Kendra	24.30%	-20.69%	3.61%
Henry	40.72%	-20.69%	20.03%
Monica	7.39%	-3.45%	3.94%
Average	22.44%	-10.34%	12.10%

Table 2.5
Average of Test Score Percentages by Quadrant

	Pre	Post	Post-Post	Average Test Percentage
Average of Low Mai (L/H and L/L)	65.08%	83.91%	74.71%	74.57%
Average of High MAI (H/H and H/L)	55.56%	81.61%	70.11%	69.09%
Average of Low Content (H/L and L/L)	53.97%	83.91%	68.97%	68.95%
Average of High Content (H/H and L/H)	66.67%	81.61%	75.86%	74.71%

Table 2.6
Average of Differences between Pre, Post, and Post-Post Test Score Percentages by

Quadrant			
	Pre/Post Difference	**Post/Post-Post Difference**	**Pre/Post-Post Difference**
Average of Low Mai (L/H and L/L)	18.83%	-9.20%	9.63%
Average of High MAI (H/H and H/L)	26.05%	-11.49%	14.56%
Average of Low Content (H/L and L/L)	29.94%	-14.94%	15.00%
Average of High Content (H/H and L/H)	14.94%	-5.75%	9.20%

Table 2.7
Total Incorrect Answers by Topic

	Incorrect Pre	**Incorrect Post**	**Incorrect Post-Post**	**Total**
Osmosis	10	9	6	25
Diffusion	11	2	5	18
Filtration	30	11	18	59
Total	51	22	29	102
χ^2 (Total)	0.311			
χ^2 (Pre/Post)	0.105			

Table 2.8
Total Incorrect Answers on Anchor Questions by Topic

	Incorrect Post	**Incorrect Post-Post**	**Total**
Osmosis	2	4	6
Diffusion	4	11	15
Filtration	2	4	6
Total	8	19	27
χ^2 (Total)	0.931		

Embedded Questions. The raw percentages for each module by student are listed in Tables 2.9 (osmosis), 2.10 (diffusion), and 2.11 (filtration) below. The overall average percentages for each module and student are listed in Table 2.12. Unfortunately, Monica and Kendra's scores for osmosis were not recorded due to a glitch in the system. As such, the trends described below may be skewed. Diffusion had the highest average score percentage (63.19%), while filtration had the lowest average score percentage (57.69%). Overall, however, there was not a high margin of difference between the modules in terms of scores, with the averages spread over only six percent. On the sections of the modules with a higher ratio of free-response to forced-choice points, students scored lower. Reasons this may have occurred are discussed below.

Table 2.9
Osmosis Embedded Question Analysis

	Manual	**Evaluation**	**Hypothesis**	**Hypertonic**	**Case Summary**	**Total**
Monica	NA					
Emma	87.50%	50.00%	37.50%	71.43%	62.50%	61.54%
Riley	75.00%	25.00%	62.50%	71.43%	37.50%	53.85%
Kendra	NA					
Henry	75.00%	87.50%	62.50%	71.43%	50.00%	69.23%
Joey	75.00%	37.50%	87.50%	71.43%	12.50%	56.41%
Average	78.13%	50.00%	62.50%	71.43%	40.63%	60.26%
Open-ended points	0 out of 8	3 out of 8	3 out of 8	3 out of 7	7 out of 8	20 out of 39

Table 2.10
Diffusion Embedded Question Analysis

	Manual	**Interpret/ Hypothesis**	**Treatment Hypothesis**	**Interpret/ Hypothesis (2)**	**Case Summary**	**Total**
Monica	60.00%	100.00%	100.00%	83.33%	45.45%	81.25%
Emma	60.00%	28.57%	41.67%	50.00%	18.18%	35.42%
Riley	100.00%	35.71%	75.00%	33.33%	18.18%	47.92%
Kendra	60.00%	100.00%	33.33%	100.00%	100.00%	81.25%
Henry	60.00%	35.71%	33.33%	100.00%	100.00%	60.42%
Joey	80.00%	78.57%	75.00%	100.00%	45.45%	72.92%
Average	70.00%	63.10%	59.72%	77.78%	54.55%	63.19%
Open-ended points	0 out of 5	11 out of 14	9 out of 12	3 out of 6	11 out of 11	34 out of 48

Table 2.11
Filtration Embedded Question Analysis

	Diagnosis	**Background/ Hypothesis**	**Parallel**	**Counter Current**	**Pre-Summary**	**Patient Summary**	**Total**

Monica	80.00%	80.00%	100.00%	75.00%	83.33%	16.67%	61.54%
Emma	80.00%	60.00%	100.00%	50.00%	50.00%	16.67%	51.28%
Riley	80.00%	20.00%	83.33%	25.00%	33.33%	41.67%	46.15%
Kendra	80.00%	100.00%	100.00%	50.00%	83.33%	75.00%	79.49%
Henry	80.00%	80.00%	83.33%	25.00%	50.00%	41.67%	56.41%
Joey	80.00%	100.00%	83.33%	0.00%	50.00%	25.00%	51.28%
Average	80.00%	73.33%	91.67%	37.50%	58.33%	36.11%	57.69%
Open-ended points	4 out of 5	3 out of 5	0 out of 6	2 out of 4	5 out of 6	12 out of 12	26 out of 38

Table 2.12
Total Embedded Question Analysis

	Osmosis	**Diffusion**	**Filtration**	**Average**
Monica	NA	81.25%	61.54%	71.40%
Emma	61.54%	35.42%	51.28%	49.41%
Riley	53.85%	47.92%	46.15%	49.31%
Kendra	NA	81.25%	79.49%	80.37%
Henry	69.23%	60.42%	56.41%	62.02%
Joey	56.41%	72.92%	51.28%	60.20%
Average	60.26%	63.20%	57.69%	
Open-ended points	20 out of 39	34 out of 48	26 out of 38	70 out of 125

Discussion

The test score analysis indicates that the modules may have had a positive effect on the students' content knowledge, as evidenced by the score percentage increase for every student between the pre and post-test. Unfortunately, perhaps due to the length of elapsed time, between the post and post-post test the students' content knowledge decreased, as evidenced by the decrease in score percentage difference. Despite the positive pre/post-test score difference, there was ultimately no statistically significant impact in the test scores as a result of the modules. This was true for both the test questions and the anchor questions. There are several possible reasons for these results: first, low sample size could have contributed to the lack of significant results. Since the sample size does not exhibit a normal curve, the usual statistical tests cannot be used to measure correlation. Another reason could be the differences between the test forms. For instance, some students took test form A for the pre-test, form B for the post-test, and form A again for the post-post test. The two different forms, although they test for the same content, contain slightly different forms of the questions. Some students may excel at one form, and not at the other. Unfortunately, this problem is not easily remedied. If all students were given the same test form for every administration of the test, then their scores may have been inflated merely as a byproduct of repetition.

Similarly, little information can be inferred from the results by breaking down the test scores by the MAI/Content score quadrants into which the participants were initially sorted. It is understandable that students who began with a low content score would develop a higher post or post-post test score, merely because they had more room to increase their understanding. Therefore, the results of this analysis may have been confounded by the fact that the pre-test was used for part of the selection criteria in the initial participant selection. The MAI was also used as part of the selection criteria to differentiate participants into score quadrants. Schraw and Dennison (1994) developed the MAI with the intention of creating an instrument that tested for both knowledge and regulation of cognition. As discussed above, students with a higher score on the MAI had higher overall test score percentages and higher overall percentage increases between the pre and post-test. This increase in tests' score percentage may have been due to higher levels of cognitive ability, and not necessarily from better understanding of the content.

In terms of the modules, there was not a high degree of difference between modules in students' overall scores. Interestingly, there did seem to be a moderate trend of better scores on sections with more forced-choice and less open-ended questions. This could be due to the nature of forced-choice versus open-ended questions. For instance, multiple-choice questions with four answers would see students answering correctly 25% of the time, regardless of understanding. However, I would like to propose another potential explanation, concerning the rubrics used to grade the open-ended questions. Developing the rubrics was an iterative process. During this process, the team of researchers and I revised each question on the rubric several times, making sure that the key was as complete as possible. For instance, a problem in the osmosis module asks the following: Based on what you have learned, summarize the relationship between solute concentrations on opposite sides of a semi-permeable membrane and the direction of movement of free water molecules. In order to get full credit for this question (3 points), students needed to include several pieces of information: they should accurately explain the relationship between higher sodium concentrations and water movement, as well as mention that more water will be necessary to bond with the sodium molecules. Additionally, they needed to mention that water would move to areas of high sodium concentration, and from an area of high to low water concentration. This is just one example, but it illustrates a clear issue. Students are expected to write about four different interconnected concepts, despite not having that specification in the question. This led to a possible scoring issue. We overinflated the scores on the forced choice responses by telling students when they were correct or incorrect, which meant that, using process of elimination, students could get the first of a series of forced-choice questions wrong, then use their processing skills to get the others correct. This has less to do with content understanding and more to do with process of elimination. At the same time, we unintentionally decreased the free response scores by not including things like the terms that students should mention to get full credit or that they should be as complete as possible in their responses. Doing this created a potentially larger difference between the free-response and forced-choice scores than what might have normally occurred.

Conclusion

In order to investigate whether the modules had any impact on students' understanding of osmosis, diffusion, and filtration, more research is necessary. It is clear, however, that the participants in this study lacked some conceptual understanding of the concepts. The average score percentages on the embedded questions were low, as were most of the test scores. Additionally, although the post-test scores showed a marked increase in conceptual understanding, the post-post test scores showed a marked decrease. This indicates that the knowledge that students potentially gained while using the modules may have been stored solely in short-term memory, rather than long-term memory. In the larger study, we will be able to run statistical tests suited to a large population. Ideally, these tests will show a stronger positive trend between the module intervention and the students' test scores.

Breaking down the test results by the MAI/Content score quadrants yielded interesting results. In future studies, this method of categorization could be very useful, especially when examining students' performance on curricular tools that are focused on cognitive and metacognitive knowledge and skills, rather than just students' knowledge of science facts. Unfortunately, investigating students' understanding of specific science concepts is complicated, especially when looked at in conjunction with innovative, but untested, computer programs. Finally, in terms of the modules, it is clear that more testing is needed in order to both accrue more data and further investigate their usefulness. As of right now, providing a simple answer to the question of the modules' usefulness is impossible. To aid this investigation, deeper research on these participants and the modules is necessary, and will be presented in future articles.

CHAPTER 3

CHARACTERIZING SECONDARY SCIENCE STUDENTS' KNOWLEDGE OF MOLECULE MOVEMENT, CONCENTRATION GRADIENTS, AND EQUILIBRIUM THROUGH MULTIPLE LEARNING CONTEXTS

In education, it is imperative to understand how students learn—specifically, how much and which types of knowledge are acquired. Learning, which is generally defined as "the acquisition of knowledge" (Mayer, 2002, p. 226), spans many areas of research in science education, a great deal of which is dedicated to understanding this learning process and the knowledge and skills developed as a result. The study reported here was designed to characterize student knowledge of three interrelated concepts: molecule movement, concentration gradients, and equilibrium. Understanding movement on a molecular level is a foundation for more advanced science topics later in the educational process, and knowledge on one of the topics informs knowledge about the two others. For example, if a student understands how molecules diffuse across a membrane, then they may be better prepared to understand how osmosis works (Friedler et al., 1987).

The concepts under investigation were represented in three computer-based modules. One module focused on osmosis, another focused on filtration, and the third focused on diffusion. These modules were designed to be used either individually (i.e., just the osmosis module) or as a unit (i.e., using all of the modules to build on each other). As such, the modules promote learning of science topics both within each module and as a whole throughout.

In this research I evaluated students' knowledge of molecule movement, concentration gradients, and equilibrium through different learning contexts (such as interviews, tests, and drawing exercises, with the modules as a primary example). The think-aloud interviews and embedded questions in the modules were administered as students interacted with simulations in the modules that illustrated molecule movement, which provided a window into students' thought processes *during* the learning experience. I used pre, post, and post-post tests, a post-interview, and a post-post free response survey, as well as drawings created by the students during the post-interview and the post-post survey, to characterize student knowledge at different stages and under different evaluations. I chose three participants and qualitatively analyzed their work, coding the data for their understanding of the scientific concepts they were expected to glean from the modules, as well as additional data trends.

The specific research question guiding this study was: How can students' knowledge of molecule movement, concentration gradients, and equilibrium be characterized in different learning contexts, including computer-based modules containing simulations? Few studies address these specific concepts, though they play a key role in many higher-level science courses, including physics and organic chemistry. In answering this research question I hope to fully characterize student learning and, secondarily, to evaluate the effectiveness of various learning contexts. Video games like those in the modules have been shown to "promote active learning, critical thinking skills, knowledge construction, collaboration, and effective use and access of electronic forms of information" (Watson, Mong, & Harris, 2011, p. 466). As science classrooms incorporate new learning contexts and forms of assessment, it is critical that educators understand the precise effects of these tools. However, as my data pool consists of only three students, my priority is to characterize learning first, and then potentially use that information to assess the value of the modules.

Review of the Literature

The following sections focus on student learning and cognition and provide an overview of how educators define these concepts and characterize knowledge. Additionally, I discuss computer simulations and provide an overview of the different types of simulations as well as an evaluation of their usefulness in the science classroom.

Student Knowledge. In the literature, the process of acquiring knowledge (cognition) is often defined as a collection of mental processes that include memory, problem solving, language acquisition and understanding, and decision-making (L. Anderson & Krathwohl, 2001). Each of the definitions available offers insight into the student learning process and all depend on the ability to evaluate or assess student learning—the primary focus of this study. Ausubel and Robinson (1969) focused on "present knowledge, which consists of the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to him at any point in time" (p. 51), while Reif (2008) defined cognition as "thoughts…learning processes and associated kinds of knowledge" (p. 4). It should be noted, however, that knowledge is not considered to be a static pool of facts:

> Knowledge is not a copy of reality. To know an object, to know an event, is not simply to look at it and make a mental copy, or image, of it. To know an object is to act on it. (Piaget, 1997, p. 20)

Rather, knowledge requires some sort of involvement on the part of the student: cognitive actions. Cognitive action, or learning, can be rote or meaningful. Rote learning means that a student "possesses relevant knowledge but is unable to use that knowledge to solve problems.

She cannot transfer this knowledge to a new situation" (Mayer, 2002, p. 227). Within the context of this study, a student who can give the definition of free water molecules but cannot explain diffusion would have accomplished rote learning. Meaningful learning, however, "occurs when students build the knowledge and cognitive processes needed for successful problem solving" and "can transfer [their] knowledge to new problems and new learning situations" (p. 227). The transfer of concepts from one module to the next and across learning contexts would be evidence of meaningful learning. Koedinger (2010) uses a similar term, robust learning, which is "learning that lasts over time (long-term retention) and that transfers to new situations that differ from the learning situation along various dimensions (e.g., superficial differences in materials and assessment events)" (p. 7).

In this study, I assessed students' meaningful learning as they progressed through three modules. The modules simulated biological processes at the molecular level, and through forced-choice and open-ended questions evaluated student progress and comprehension. Focusing on student knowledge of molecular movement, concentration gradients, and equilibrium gave me an opportunity to assess how different modules and tests allow students to share and expand their knowledge. For example, students' demonstrated knowledge of molecule movement on the multiple-choice tests may be very different from their knowledge of molecule movement on the free-response questions of the modules. This has implications for the development of future assessments to fairly and accurately reflect student learning. My goal was to understand how student knowledge is characterized in different learning contexts, thus I focused on student responses to various contexts and assessments.

With respect to students' understandings of molecule movement, Sanger, Brecheisen, and Hynek (2001) found that students have difficulty understanding osmosis and diffusion. More specifically, Friedler et al. (1987) found that students hold misconceptions about the process of osmosis:

> (1) The most frequent explanation offered to osmosis is a desire or drive towards equalizing concentrations.' (2) Hardly any student uses the concept 'water concentration'. (3) Most students fail to realize that in dynamic equilibrium water molecules keep moving. (4) Students have special difficulty in understanding osmotic relations in plants. (5) Many students have difficulty in grasping solute-solvent and concentration-quantity relations. (p. 541)

Thus this study fills a gap in the literature by covering a relatively underserved area (scientific knowledge) through three important, understudied, and interrelated concepts: molecule movement, concentration gradients, and equilibrium, as opposed to the traditional single topic. As different learning contexts reveal continuing misconceptions and barriers to understanding, this research will assist science educators in more thoroughly covering and assessing these critical topics.

Computer Simulations in the Science Classroom. The modules in this study are simulations designed to enhance learning by providing visualizations of molecular-level processes. For the purpose of this study, they provide a learning context to evaluate student knowledge. In general, computer programs that provide visualizations aid "student understanding of complex processes because [visualization] assists in the conversion of an abstract concept into a specific visual object that can be mentally manipulated" (McClean et al., 2005, p. 170). Providing visuals of processes that occur at the molecular level can assist students in developing their knowledge of these processes. Although the modules are complex and include much information through simulated experiments and exercises, research has shown that "by using well-designed visual tools, students can digest large amounts of information in a relatively short time and construct their own personal visualization of a process" (McClean et al., 2005, p. 170). Additionally, as will be discussed below, studies have shown that students hold various misconceptions about osmosis, diffusion, and filtration. Theoretically, "~~these~~ animations have the potential to make it easier for students to understand difficult science concepts" (Thatcher, 2006, p. 9).

The modules used in this study are educational video games that feature simulations designed to help students understand scientific concepts. Computer simulations are defined as "a program that contains a model of a system . . . or a process" (De Jong & Van Joolingen, 1998, p. 180). There are two types of computer simulations: those that illustrate "conceptual" modules, and those that illustrate "operational" modules: "Conceptual models hold principles, concepts, and facts related to the (class of) system(s) being simulated. Operational models include sequences of cognitive and noncognitive operations (procedures) that can be applied to the (class of) simulated system(s)" (p. 180). The modules used here are conceptual because they feature the simulated processes of osmosis, diffusion, and filtration. Using these modules, students engage in inquiry-oriented activities at their own pace in a self-guided manner.

All of the modules used in this study are designed not only to develop students' knowledge of osmosis, diffusion, and filtration, but to stimulate students' higher order learning processes by requiring responses that demonstrate greater depth of thinking and knowledge than that required by typical multiple choice answers. Students are expected to explain and rationalize the choices they make. All of the modules are organized as a narrative, taking students through a story from start to finish. Research indicates that "animations and graphics with a spoken or written narrative are more effective than those lacking a narrative" (O'Day, 2007, pp. 217–218).

The combination of all of these components in the modules creates a very powerful classroom tool. In a study designed to assess students' knowledge of osmosis and diffusion, Sanger, Brecheisen, and Hynek (2001) found that:

> …students who viewed computer animations depicting the molecular processes occurring when perfume particles diffuse in air and when water osmoses through a semi-permeable membrane developed more accurate conceptions of these processes based on the particulate nature and random motion of matter. (p. 108)

These findings suggest that the modules in this study can potentially impact students' understandings of osmosis, diffusion, and filtration. Through the use of stories, detailed computer graphics, and gameplay style learning, students are not only able to engage in a self-directed science lesson, but gain valuable knowledge through entertainment. More importantly, for the sake of this study, the modules provide a unique learning context within which we can examine student knowledge in various situations and through various assessments. Additionally, the modules, in conjunction with the think-aloud interviews, offer a venue in which to explore student knowledge and thought-processes in real time, as opposed to after a task. Lastly, this study is truly the first of its kind, as the modules in this study are largely untested and are still undergoing development.

Methods

In the following sections I discuss the curricular context, the participant selection, and data collection and analysis. I then describe the results of the study in terms of student responses to the modules and various learning contexts.

Curricular Context. Each module in the study has a specific storyline. In the osmosis module, students act as a veterinarian treating a calf with cerebral edema. Clark, the calf, has ingested too much water and lowered his blood sodium level. Students choose from a hypertonic, hypotonic, or isotonic solution treatment, taking various measurements within Clark's brain to assess his progress. Throughout the module, students study osmosis, concentration gradients, and equilibrium. In the diffusion module, students are charged with helping a woman exposed to toxic chlorine gas. They provide treatment in the form of oxygen, diuretics, and corticosteroids while learning about three concepts connected to concentration gradients: concentration difference, diffusion distance, and surface area. The filtration module simulates a patient undergoing dialysis treatment. Students take an in-depth look at the process of dialysis and filtration, building on their knowledge of concentration gradients by learning about parallel versus countercurrent flow.

Each module had three concepts in common:

A. Molecule movement: Molecules travel across a selectively permeable membrane, a process that is central to osmosis, diffusion, and filtration
B. Concentration gradients: Concentration gradients drive the process of molecule movement across membranes and, during this process, molecules move from an area of high concentration to low concentration
C. Equilibrium: Systems tend toward equilibrium and, once it is reached, net flow of molecules ceases (although movement of molecules across membranes continues in equal amounts)

These three concepts fit into the overarching principle of molecular study. Diffusion is the movement of molecules from a high concentration to a low concentration. This movement occurs as a result of the random collision between molecules. Molecule movement constitutes diffusion, the movement of water across a membrane specifically is considered osmosis. Concentration gradients are closely related; they affect how molecules move and in what direction. In osmosis, this movement is driven by a concentration gradient, wherein water moves from an area of high concentration to an area of low concentration. This movement occurs because of solute concentration, and although water moves from high to low areas of concentration *of water molecules*, it moves from low to high areas of concentration *of solvent molecules,* a distinction that students often find confusing. A key aspect of this process that is covered in the modules but not usually covered in high school biology classes is that of free water. Free water molecules are water molecules not bound to solutes—different concentrations of solute molecules lead to different concentrations of free water molecules. This is because in areas of high solute concentration, more free water binds with the solute molecules, causing a decrease in free water. Therefore, during osmosis, water molecules actually move from an area of high *free water* concentration, to an area of low *free water* concentration. This may seem like a small difference, but the implications that stem from this difference in understanding are wide and far-reaching. Using the concept of free-water molecules, instead of water, brings a chemistry aspect to biology that helps students understand the fundamental processes of osmosis and diffusion.

Filtration also utilizes these mechanics, but during the module students focus more on the size of the pores in the selectively permeable membrane, which determines which molecules can pass through the membrane. Equilibrium denotes the final step of the process in any of these three forms of molecular movement. Once equilibrium has been reached, the *net* flow of water molecules ceases, but molecules still travel through the membrane in equal amounts. Molecule movement forms the basis for every aspect of this module. It is influenced by concentration gradients, so students must understand their function to determine how molecules will move.

Similarly, equilibrium is the ultimate end product of molecule movement, so a strong understanding of that topic provides necessary knowledge on *why* molecule movement occurs.

Participant Selection. Three students—Emma, Henry, and Riley (all names are pseudonyms)—participated in this study. Each of the participants was a ninth grade honors biology student. Emma, fourteen, said that she's "not the type of person where it comes naturally, like I'm not like a logical thinker" (Emma, I4, lines 238-239). Despite not thinking highly of her science skills, she said that she didn't have to study a great deal for science, but that if she did, "[she would] do good. Like really good" (lines 246-47). Henry's favorite subject was math. Also age 14, he did not seem too interested in science. Riley, 15, liked school. His favorite common course was chemistry: "It's difficult, but I like how interesting it is about like, the elements and what we're made of and stuff like that" (Riley, I4, lines 232-234). Although I originally used six participants, the data collection from the osmosis module for three of my participants did not record. To avoid compromising the internal validity of this study, which relies heavily on having data from various educational contexts and levels of student knowledge, I chose to use only those students who had complete sets of data. Doing so provided a more accurate representation of students' knowledge. Refer to Raven (2013) for the full participant selection process and the school/classroom context associated with the larger study.

Data Collection. Multiple data sources were used in this study, including pre, post, and post-post tests, which were designed by the research team associated with a larger study. The pre test contained 21 multiple choice items designed to assess students' preliminary knowledge of osmosis, diffusion, and filtration, while the post and post-post tests contained eight additional items designed to test students' knowledge of module-specific content. There were two forms of the tests. Students alternated between test forms for each testing day, so those who took form A for the pre test then took form B for the post test, then form A again for the post-post test. This was intended to prevent an artificial impression of knowledge that was in actuality a result of rote repetition.

Each of the modules contained embedded forced-choice and free-response questions. Most of the forced-choice questions provided students with immediate feedback—the module does not allow students to move forward until the question has been answered correctly. Forced-choice questions are graded as follows: if the student answers correctly the first time, full points are given. If the student answers incorrectly the first time, no matter how many tries it takes to eventually answer correctly, no points are rewarded. The open-ended questions do not provide feedback. They prompt students to explain their reasoning, but these responses are not graded within the module. Rubrics for each module are included in Appendices B (osmosis), C (diffusion), and D (filtration).

To access students' knowledge and cognitive processes, I utilized a think-aloud protocol (van Someren, Barnard, & Sandberg, 1994). While students used the modules, I sat beside them and asked questions. In particular, I asked students to tell me what they were thinking as they answered the embedded module questions. For instance, as students answered questions, I asked them to tell me why they answered the question that way or what made them choose that answer. Additionally, if students became silent, I prompted them to continue talking, usually by saying, "Tell me what you're thinking here." These conversations were audiotaped, and I produced transcripts from the recordings. After completing all modules, students were interviewed. The post interview and post-post free response surveys were used for two purposes: first, to triangulate the think-aloud interview results, as the use of multiple sources of data can be used to triangulate data collection (Merriam, 1995), and second, to increase the internal validity of the study as a whole, since having a variation of sources strengthens internal validity (Creswell, 2005). The questions in the post-interview (see Appendix E) had students summarize the knowledge they developed during their use of the modules, and were both structured and focused (Patton, 2002; Yin, 2009), while the post-post free response survey questions were designed to determine whether the knowledge and processes used during the modules were short-term or long-term memory artifacts, since the post-post free response survey was administered to students almost two months from the start of the unit (O'Day, 2007). Any knowledge retained at the time of the post-post response could safely be considered as a long-term artifact. The data collection calendar is shown in Table 3.1.

Table 3.1
Data Collection Methods and Timeline

Data Collection Method		**Data Collection Timeline**					
		Oct. 9^{th}, 2012	Oct. 22^{nd} to Oct. 26^{th}, 2012			Oct. 29^{th} to Nov. 2^{nd}, 2012	Dec. 12^{th}, 2012
Pre-test		X					
Osmosis	Embedded module questions		X				
	Think-aloud interview		X				
Diffusion	Embedded module questions			X			
	Think-aloud interview			X			
Filtration	Think-aloud interview				X		
	Embedded module questions				X		
Post-test						X	

Post-interview/Drawings					X	
Post-post-test						X
Post-post-free response survey/Drawings						X

Data Analysis. I used a criterion-based sampling method (Merriam, 1988) and chose questions and selections from the interviews specifically to categorize student knowledge on the three concepts. This approach resulted in the analysis of five questions each from the pre, post, and post-post tests that evaluated students' knowledge of the concepts. For instance, the following question tests knowledge of concept A (Molecule movement):

1. The movement of water molecules across a selectively permeable membrane is called:
    a) Diffusion
    b) Filtration
    c) Homeostasis
    d) Osmosis

I graded students' answers using the test keys developed for the study.

For the embedded module questions, I used the same process, selecting questions that covered the concepts chosen for this study. In doing so, I selected four questions from each module. The questions were a mixture of forced-choice and open-ended formats. I graded these questions using the rubrics that included certain key terms that must be mentioned and looked for specific connections between concepts to demonstrate meaningful knowledge. In evaluating the think-aloud interviews and post-interview, I first coded the transcripts by looking for sections where students specifically discussed an important concept. For instance, if a student mentioned the direction of water movement in terms of osmosis, I noted the excerpt as pertaining to concentration gradients. After identifying and organizing these excerpts, I used an open-coding method (Strauss & Corbin, 1990). This procedure "includes discovering categories and category naming" (Castro, Kellison, Boyd, & Kopak, 2010, p. 348). I looked for themes both individual to each student and common to all of the students. Doing so revealed several misconceptions common to all of the participants, as well as some unique themes. Lastly, during the post-interview and on the post-post free response survey, I asked students to draw pictures illustrating osmosis. I analyzed these drawings as well, coding the illustrations for students' knowledge of the three concepts of molecular movement. My coding focused on level of detail and level of accuracy in an attempt to qualitatively assess their drawings.

Results

In this section I describe the experiences each student had with the modules. This is primarily to characterize their learning across different learning contexts and gather data on knowledge of the concepts. I then evaluate the impact of the modules in the discussion section.

Knowledge Characterization: Riley. At the beginning of the unit Riley had limited knowledge of molecular movement, choosing the incorrect answer on three out of five questions on the pre-test (see Table 3.2). The two questions he answered correctly focused on selectively permeable membranes. After the pre test, Riley's test results were varied. For instance, on question 1, he chose the correct answer on the pre and post-post test, but the incorrect answer on the post-test, while on question 3, he chose the correct answer only on the post-test. The inability to transfer this knowledge across different assessments indicates rote, and not meaningful knowledge, of the concepts, both before and after the unit. During the osmosis module, he did not answer any of the key questions concerning molecule movement correctly. During the think-aloud interview for that module, when asked to explain why water was moving in a certain direction, he had no concept of the explanation:

R: Um, I'm not sure this is right, but I'm thinking, like, the pressure's really high and it's forcing the free water out. —long pause—Whoa! —long pause—I have no idea with this.

Interviewer (I): That's OK. Best guess?

R: I don't know. Like, I don't even know what to guess. (Riley, I1, lines 59-63)

Table 3.2
Riley's Pre, Post, and Post-Post Test Results

Question and Correct Answer	Pre test	Post test	Post-post test
(1) The movement of molecules across a selectively permeable membrane is called osmosis.	1	0	1
(2) Homeostasis occurs when the biological processes within an organism result in equilibrium.	0	1	1
(3) Increasing the surface area of an alveolus would increase the rate of diffusion for oxygen.	0	1	0
(4) A membrane that allows certain solutes to pass through but not others is called semipermeable.	1	1	1
(5) The process by which solutes are exchanged across a semipermeable membrane separating two different solutions being pumped in opposite directions is called countercurrent exchange.	0	1	1
	0=Incorrect, 1=Correct		

However, Riley then identified the correct direction of water movement, demonstrating an ability to interpret the visualizations from the module after watching a simulation of blood flow in the brain, but not necessarily an ability to apply that knowledge:

I: …which way is that free water moving?

R: Uh, out of the blood vessel.

I: And into the…

R: Into the, like, matrix. (Riley, I1, lines 76-79)

Near the end of the osmosis module, Riley discussed what he believed to be the impetus for the water molecule movement, which was based on a definition that did not reflect any idea presented in the module rather than any concrete knowledge development from the module. He explained:

> R: So—short pause—if the, the free water extra molecules were to increase—short pause—um it would cause the opposite to…well actually…that's really slow.
>
> I: Yeah I know.
>
> R: It would increase and it would push through the pressure and, not the blood pressure, blood vessel, and increase the pressure. (Riley, I1, lines 209-213)

Although he was able to identify the correct direction of free water movement midway through the module, he did not attribute that movement to the concentration gradient. Rather, he said that the amount of water in the cell created so much pressure that it forced the water out. Although osmotic pressure is a related concept, it is a result of molecule movement, not the cause of molecule movement.

During the diffusion module, Riley chose the correct answer on the three forced-choice questions, but failed to provide a correct answer on the open-ended question, demonstrating a lack of comprehension of molecule movement and concentration gradients. For instance, Riley could not explain the concentration gradient, a key aspect of diffusion. His confusion is evidenced in the transcript:

> I: Alright, so what was the one about concentration difference talking about?
>
> R: Um, it was about how, there's like a higher concentration, how, like, is there a difference in time like, crossing over to the other side. And if there's like a lower one, would it be faster or something.

I: OK, so the relationship is…lower concentration difference—

R: And higher diffusion rate. (Riley, I2, lines 1-9)

In this excerpt, Riley indicated that a lower concentration difference creates a higher diffusion rate, although the opposite is true.

In the filtration module, Riley answered almost no questions correctly on the first attempt, possibly a result of difficulties understanding the related concepts preceding it. In an open-ended question asking why diffusion occurred in all regions of the filter, he once again mischaracterized concepts A and B, indicating that pressure causes osmosis and molecular movement: "Becuase [sic] the dialysate is being pumped upward forcing all of the urea out withh [sic] keep the albumin potassium" (Riley, M3). Despite having completed two previous modules, he asked:

R: —long pause—What's the concentration gradient?

I: I'm sorry, what?

R: The concentration gradient…I forgot what that was. (Riley, I3, lines 21-23)

Riley was able to answer questions pertaining to concentration gradients later in the modules. He correctly explained which direction molecules were moving, indicating that, possibly, he had an understanding of the concept but not the vocabulary:

R: Well since last time the uh, whatchacallit, the concentration gradient, it separated them. And in this one they're all separated, so I clicked "all the —"

I: Gotcha. And so with the, whether it's diffusing into the blood or the dialysate, how'd you choose that?

R: Um, same as last time. It's going from high to low, and so is that one.

I: OK.

> R: —long pause— I don't even know what it's talking about. —long pause—
>
> I: It's OK. What made you guess that one instead of the other one?
>
> R: Um, actually pretty sure on this one. We want potassium in the blood but not like, too much, so it's going to keep on diffusing until it's reached like, an equilibrium like it is, or so it's at like a healthy level…count. (Riley, I3, lines 54-70).

During the post-interview, however, Riley's answers showed no evidence of this understanding:

> R: Um, with the flowing just straight through those like, filter tubes, it, um, it took away things that it shouldn't have, because it was just, it couldn't get through the barrier. But when you put the dialysis stuff, and you put it up the tube, I'm not sure but it helped get something, it helped keep something in the blood. Like, it was easier for it to stay in there. It wasn't being filtered out. (Riley, I4, lines 86-92)

Additionally, the misconceptions about concentration gradients and the impetus for molecule movement that he held in the osmosis module were still present in his explanations during the filtration module, saying that the reason the water was moving was: "It was like the blood vessel was pushing something out of it" (Riley, I4, line 44).

Riley's scores on the post and post-post test questions increased, getting four out of five correct during each administration, but his remarks and misconceptions during the interviews and written responses in the modules indicate a lack of meaningful knowledge. The drawings that Riley provided during the post-interview and post-post free response survey support these findings, as, although they were detailed, his lack of understanding was evident. Riley's drawing showed the aquaporins in the selectively permeable membrane, the sodium molecules, and the free water that surround them, but he could not indicate which direction the water would move. When pressed, he indicated that the water would move in the direction of less sodium, a guess clearly showing a lack of understanding. On the post-post free response survey, the drawing had less detail, and showed no movement of water.

Riley was able to produce correct answers in multiple-choice scenarios after the module, however, this was more indicative of rote knowledge than meaningful knowledge. His persistent misunderstanding of key concepts of molecule movement that form the base for diffusion, filtration, and osmosis was essentially unaffected by the modules, and very little long-term knowledge growth occurred.

Knowledge Characterization: Henry. Henry began the unit with a perfect score on all of the pre-test questions, indicating a strong base of knowledge on the concepts (see Table 3.3 below). During the osmosis module, he showed a similar amount of understanding—getting half of the questions correct despite being introduced to new topics. He showed clear understanding of concentration gradients in both the embedded questions: "Free water is moving out of the blood, because there is more sodium in the matrix, so there is water going into the matrix to break down the sodium" (Henry, M1), and in the think-aloud interview:

I: So there's more sodium in the matrix…

H: Mm-hmm. And so the water is going to flow out of it to break it down, and that's causing problems because it's going to inflame the brain. Swell. (Henry, I1, lines 80-83)

Henry presented knowledge of key science topics in both written and verbal learning contexts. He did, however, hold some misunderstandings. Henry could not understand the interaction between water molecules and solute molecules, indicating a lack of comprehension of concentration gradients and equilibrium. He had difficulty choosing a solution to address the calf's condition because he was unsure how molecules interacted, instead focusing on the amount of water involved.

I: So because there's more water in Clark's brain, you're saying the hypotonic will be more effective, because there's less water in it. Right?

H: Because we don't want him to go even more water. —short pause—And then there's going to be less so it's going to diffuse into it. It's that because of the—short pause—OK. It's going to be like that, because there's a lot of out of the vessel, and in the vessel there's not a lot of water. So the less water he gets, I guess, is going to help him, so hypo. Oh. OK. (Henry, I1, lines 135-144)

Table 3.3
Henry's Pre, Post, and Post-Post Test Results

Question and Correct Answer	Pre-test	Post-test	Post-post Test
(1) The movement of molecules across a selectively permeable membrane is called osmosis.	1	1	1
(2) Homeostasis occurs when the biological processes within an organism result in equilibrium.	1	1	1
(3) Increasing the surface area of an alveolus would increase the rate of diffusion for oxygen.	1	0	0
(4) A membrane that allows certain solutes to pass through but not others is called semipermeable.	1	1	1
(5) The process by which solutes are exchanged across a semipermeable membrane separating two different solutions being pumped in opposite directions is called countercurrent exchange.	1	1	0
	0=Incorrect, 1=Correct		

Additionally, although Henry understood that equilibrium resulted in an even amount of molecules, he did not link that to the net flow of water, saying: "So wait, most of it's out of the vessel? Like it says? And so it's going to go in equilibrium, because diffusion and osmosis always deal with like, getting to the same" (Henry, I1, lines 156-158).

In the diffusion module, Henry received almost full credit, missing only one out of ten points. Surprisingly, given his score on the embedded questions, his explanation of the link between concentration difference (concept B) and the rate of diffusion indicates a lack of understanding and how knowledge can be characterized very differently depending on the learning context:

> H: I'm thinking about decreasing the concentration because this is more, it would, it would increase the rate so…
>
> I: Why did you think it was that one?
>
> H: Um, I don't know… (Henry, I2, lines 6-10, 14-15)

Henry's scores in the filtration module decreased. He earned only four our of eleven points on the embedded questions, mischaracterizing the concentration gradient mechanism (concept B) of counter-current flow, writing that it "made the diffusion occur in all regions, because it made the urea go more into the dylasate [sic]" and that "The countercurrent was better, because it made filtration and diffusion easier" (Henry, M3). Although he seemed to misunderstand while answering the embedded questions, his explanation in the interview indicated deeper understanding of concept A and B:

> I: So… how did you decide on those things, how'd you know they were right?
>
> H: I just knew they would work.
>
> I: Good answer.
>
> H: Um, just because like, these like—short pause—the, if it's like the same, they don't diffuse into each other. But if the blood has more than the di…I don't know what that is.
>
> I: Dialysate?
>
> H: Yeah. Then it's going to diffuse into it.

I: Gotcha, OK.—long pause—What are you thinking?

H: I'm thinking like, there's no concentration gradient so that's why they stayed the same. (Henry, I3, lines 50-62)

Clearly, Henry understood that the concentration gradient was the impetus for molecule movement, even if he could not understand exactly why the concentration gradient occurred (concept B). He did, however, understand that equilibrium (concept C) meant that "the concentrations will stay the same," even if the molecules did not stop moving (Henry, M3).

In the post-interview, he started to incorrectly explain concepts that he had understood and tested well on within the modules and pre-tests in a written context:

I: And what is the definition of diffusion?

H: Um, the movement of particles from a low concentration to a high concentration. (Henry, I4, lines 57-59)

He identified the wrong direction for molecule movement in the diffusion module, then, when explaining the illustration of osmosis, said that it looks like, "a random, random drop of water and it's going to like a small area" (Henry, I4, lines 168-169). Although time may have been a factor in Henry's lack of understanding, it is also possible that, without the visual reference of the modules, Henry could not illustrate his deeper understanding. The post-interview did not provide any visual reference from the modules, indicating that Henry's understanding may be linked to visualizing concepts or reading questions, rather than strict verbalization. Henry's drawing further supports this difference in learning contexts, as it was the least detailed of the three participants, and did not show a membrane, sodium molecules, or water molecules. Instead, he drew a few abstract shapes with arrows going from the larger to the smaller shape. Although he seemed to understand that water moved from an area of high to low concentration, he did not illustrate the connection to sodium molecules. He did not draw osmosis on the post-post free response survey, indicating that ultimately his long-term knowledge of this topic was relatively limited.

Knowledge Characterization: Emma. Emma began the unit with four out of five correct answers on the pre-test (see Table 3.4); her only incorrect answer related to countercurrent flow.

Table 3.4
Emma's Pre, Post, and Post-Post Test Results

Question and Correct Answer	Pre-test	Post-test	Post-post Test
(1) The movement of molecules across a selectively permeable membrane is called osmosis.	1	1	1
(2) Homeostasis occurs when the biological processes within an organism result in equilibrium.	1	1	1
(3) Increasing the surface area of an alveolus would increase the rate of diffusion for oxygen.	1	1	0
(4) A membrane that allows certain solutes to pass through but not others is called semipermeable.	1	1	1
(5) The process by which solutes are exchanged across a semipermeable membrane separating two different solutions being pumped in opposite directions is called countercurrent exchange.	0	0	1
	0=Incorrect, 1=Correct		

In the osmosis module, Emma received only three out of eight points, but understood why water molecules flowed in a certain direction, writing that, "They're moving to where the concentration of sodium is higher" (Emma, M1). Like Henry, Emma seemed to alternate between understanding this movement and mischaracterizing it (concepts A and B):

> E: Oh, OK. So concentration would—long pause—oh, it would decrease because they like, attach to the salt when it breaks it apart. —long pause— Um, —short pause—I do

not think they would, because they can't go through if they're not water, or something. I don't know. —long pause—Oh my god.

I: It's OK, what do you mean?

E: Like it's the um,the aqua-porous things only water can go through. But if they're attached to the salt they wouldn't be able to. But they're not all attached, so never mind. (Emma, I1, lines 19-29)

In this case, Emma seemed unable to link the visualizations that the module provided to her answer to clarify her knowledge. On the next question, Emma completely reverses her answer, figuring out the reason for the molecule movement and how concentration gradient influences the movement:

E: This picture? So that's in the blood vessel, that's outside of it. And there's more sodium outside of it.

I: So, that question…

E: It's um, hypotonic, because there's less inside the blood.

I: Nice. —short pause—

E: And they'd move to a higher concentration. (Emma, I1, lines 45-51)

In addition to reversing her answer, Emma uses the module illustration as justification for her reasoning, something she was not able to do on the previous questions, perhaps due to the fact that the illustration was in front of her as she answered the question. Just a short while later, however, while answering a question about the direction water molecules were moving, Emma became confused:

I: So what does that mean?

E: Um, —short pause—like what do you mean?

I: Well you said they moved out because there was more sodium than in the vessel, but why would that mean they would move out?

E: Oh because they would —short pause—because water moves to where there's a higher concentration.

I: Gotcha, a higher concentration of…

E: Of the sodium? I guess of anything. (Emma, I1, lines 60-67)

Again, Emma reverts to her first answer. These excerpts paint a clear picture of Emma's misconceptions of molecule movement and concentration gradients. In the second excerpt, she indicated that the water will move to a higher concentration of sodium, and then reversed that statement in the third excerpt. Her confusion was possibly a result of the different visualizations provided by the modules or the ways in which the questions were phrased. Additionally, her inability to make up her mind indicates that Emma's understanding, while sometimes correct, may have been rote instead of meaningful, and not transferable across contexts.

In the diffusion module, Emma only received three out of nine points, and in the think-aloud interview, her responses indicated a lack of understanding across learning contexts. In response to a question on the rate of diffusion and how it is affected by the concentration of molecules on either side of a membrane, she said:

E: Oh, okay. — long pause — Um,—short pause —so, I think it decreases. Because, like, the more that was on the left side, the less moved to the right side.

E: Oh, so…Oh so I guess it means it diffuses faster, since those are lower seconds. Okay. I didn't see that.

E: …I guess as you increase concentration difference…I'm not really sure what that's showing. (Emma, I2, lines 12-14, 22-23, 32-34)

Her performance on the filtration module matched her performance on the others, receiving only three out of nine points on the questions. On a question asking why countercurrent was more effective than parallel flow, she wrote: "There was more of a concentration gradiant [sic]?" (Emma, M3). Her response indicated both slight understanding of concept B and a lack of confidence in the answer, and her explanation in the think-aloud interview supported this slight understanding:

> I: Ok, so it was both.—long pause—What made you choose that it was going from the blood to the dialysate?
>
> Um, because it's higher here and it's lower here, it just naturally goes from high to low.
>
> I: Gotcha.
>
> E: Same here. And then this one will be equal, because they're equal. That's called, equilibrium. I think. (Emma, I3, lines 31-38)

Additionally, although Emma seemed to understand equilibrium (concept C), she did not know that molecule movement does not cease, stating that: "…since they're concentrations are equal it won't pass through, and then, these will because they're so low because they're not equal, I think" (Emma, I3, lines 7-9).

Unfortunately, the partial understanding that Emma showed in the last module were not indicated in the post-interview. In discussing hypertonic solutions, which connects to concept B, she said:

> E: Hypotonic is when there's more solution inside the cell, so all the water goes inside and it swells. Then hypertonic there's more solution outside the cell, so the cell will shrink because all the water goes to the outside. (Emma, I4, lines 46-50)

This is incorrect, as the water would move into the cell, not out of it. However, in her explanation of her illustration, she correctly explained the concept:

> I: Could you draw the free water, or tell me where it would be?
>
> E: Um, it would move to the higher concentration.
>
> I: Gotcha. And do you know why?
>
> E: Um because it wants to be equal. So if there's more sodium here, there's less water. And so, and if there's less sodium here there's more water, so if you even it out, or if it moves to where there's less water it'll even out. Because all things want to be equal. (Emma, I4, lines 210-216)

This difference in explanations indicates that Emma may be dependent on visualizations. When using only a verbal explanation, Emma incorrectly explained equilibrium (concept C) and concentration gradients (concept B). However, when using a picture that she drew and could use as evidentiary support, Emma correctly explained concentration gradient and equilibrium. Emma's consistently partial knowledge and cognition is supported by her test results and drawing. She received the same score on all three test administrations, getting the same question incorrect on the post-test as the pre-test, then correcting that question but getting another wrong on the post-post test. However, Emma showed that she understood the process of molecule movement and concentration gradients in her drawing. She placed the free water on the side of the membrane with the most sodium molecules, showing she understood that water moves from an area of high to low concentration of water. She repeated this drawing on the post-post free response survey with the same level of detail. These results indicate that Emma had a long-term understanding of all of the concepts, but mischaracterized the concepts depending on the learning context.

Analysis Commonalities

Looking at the three analyses together illuminates three main topics that students have misconceptions about molecule movement, concentration gradients, and equilibrium. First, each student mischaracterized the direction of molecule flow several times. The tests and modules were designed to reinforce this concept, but students perpetuated one of the two following misconceptions: either that solvent molecules move from an area of low to high concentration of solvent molecules, or that solvent molecules move from an area of high to low concentration of solute molecules. Second, in terms of molecule movement, both Riley and Henry characterized the impetus for this movement as pressure (i.e. there were too many molecules in the cell so they were forced out by the pressure). Although osmotic pressure is a scientific concept associated with osmosis, it is *caused by* osmosis, not *the cause of* osmosis. Additionally, the actual impetus for molecule movement in regards to the modules has to do with the concentration gradient, and has very little to do with pressure. Third, although all of the students seemed to understand that equilibrium meant equal, they did not understand that molecule movement does not cease once equilibrium is reached. Rather, molecules continue to move across the membrane, but the *net flow* of water ceases. For example, consider the following quote from Emma: "…since they're concentrations are equal it won't pass through, and then, these will because they're so low because they're not equal, I think" (Emma, I3, lines 7-9). She indicated here that, although she understood what equilibrium means, she did not understand what happens in terms of molecule movement once equilibrium has been reached.

Both Riley and Henry also showed an inclination to ascribe human-like characteristics to molecules, personifying them:

I: So…how'd you decide "from matrix to blood"?

R: Yeah, —short pause— um, I noticed there's a lot in here, so I'm thinking they might want to just ease out into that one… (Riley, I1, lines 34, 37-39).

and:

I: So how'd you decide on that net free water movement one?

R: Um, since pretty much all the water is trying to get out, to balance it and make it equal where it's not like, too much pressure on the matrix, and in the blood vessel. (Riley, I1, lines 178-183)

This tendency has been studied, specifically, in regard to science education, and researchers note that "…use of anthropomorphism and animism can be a useful aid to students' understanding and learning in science" (Kallery & Psillos, 2004, p. 292). Zohar and Ginossar (1998) add that anthropomorphic explanations are popular within biology for several reasons:

> (a) The physical structure of living organisms is usually adapted to their survival; therefore, living organisms seem goal-oriented. (b) People tend to project from their own personal experiences to other circumstances. Thus, they tend to project from their own conscious aspirations, goals, and aims to phenomena they perceive in the world. This tendency results in anthropomorphic reasoning. (c) Anthropomorphic/teleological explanations have apparent explanatory value. (p. 680)

As the modules utilize a narrative structure designed to make students engage with the content, it is not surprising that they would assign anthropomorphic explanations to the objects within the narrative. Additionally, as this type of explanation can be a useful tool, this tendency indicated the development of a cognitive strategy.

It is clear, however, that, despite their performance on the forced-choice portions of the modules and the tests, all participants misunderstood aspects of each of the three main concepts associated with molecule movement. The post-interview showed that the misconceptions persisted despite the modules, and that the scores on the tests and modules were not indicative of knowledge or cognitive understanding. Measuring whether students displayed cognitive growth as they progressed through the modules would be difficult, if not impossible. With such a small number of students, making such a broad judgment is irresponsible. It seems likely, however, that, even if students did not progress in their knowledge or cognition *throughout* the modules, they may have progressed *within* modules. For instance, Riley, near the beginning of the third module, asked, “What’s the concentration gradient?” (Riley, I3, line 21). Later in the module, however, Riley explained it in context upon being asked how he chose the correct answer (see Riley’s Characterization of Knowledge). Using this evidence, we can conclude that the modules, at least in some respect, helped the students understand the content in certain contexts. Even though this positive cognitive development may not have carried through the unit, the individual learning trajectories illustrate some understanding as the students progressed.

In terms of the learning contexts, the knowledge displayed differed in the context of varying evaluations. Their answers on multiple choice questions were more often correct than their answers on open-ended questions, but this merely could be due to the nature of forced-choice versus open-ended questions. When answering multiple-choice questions with four answers, students could guess correctly 25% of the time. This level of guessing on open-ended questions with such a high score payoff is impossible. It is difficult, therefore, to attribute student success to knowledge development alone, when other factors such as assessment method comes into play.

As a final point of discussion of my analysis, I would like to address the possible role that I had in my participants’ responses. In other words, did having students participate in the think-aloud interviews while using the modules prompt them to reveal ideas that might not have been revealed without the required verbalization aspect? Additionally, does this impact their results from the modules? I would like to emphasize, once again, that I am attempting to characterize how the different learning contexts (modules, tests, and drawings) affect the presentation of knowledge. My discussion of the modules is primarily to illustrate this understanding and present an alternative learning context, not to evaluate how the modules shape their understanding, though some conclusions about their effects can be drawn from the data.

During the think-aloud interviews, I did my best to maintain a neutral tone and avoid giving any feedback, positive or negative, in my responses. When students asked questions, I tried to avoid answering, instead asking them to think about it again or put the question in their own words. Therefore, while asking the students to verbalize their thoughts during the modules may have affected how the modules shaped their understanding, the verbalization mainly served to provide a different learning context (verbalizing versus writing) that could be analyzed. Using the think-aloud interviews allowed me to understand their thought processes and better characterize faulty logic behind any misunderstandings.

Discussion

The results of my analysis show several clear differences in the characterization of students' cognition over multiple contexts. On forced-choice questions versus free-response questions, the differences were most obvious. Forced-choice questions in this study provided a more concrete measure of rote learning (what students remember) while free-response questions elicit more explanatory answers, signifying meaningful learning. Of course, the move from rote to meaningful learning came with score alterations. Overall, the students seemed to have more knowledge of the three science concepts on forced-choice questions than they did on free-response questions. This may be partly due to the nature of forced-choice questions, as students can potentially score correctly without having correct knowledge. The free-response questions embedded within the modules, on the other hand, may also suffer from underinflation and scoring bias due to the rubrics. In order to receive full credit on a question, students must include every detail specified in the rubric, despite the questions not being worded to elicit that specific response.

A difference in characterization of knowledge is also clear in written forms of communication versus verbal forms. Students' verbal explanations of the three concepts often differed greatly from their written responses. Often, these two contexts were at odds with one another, with students' answering correctly on the written form and incorrectly upon verbal elicitation, or vice versa. I cannot be certain of the reason behind this difference; it is possible that my participants were nervous about being verbally interviewed or about my observation of their work. It is also possible that the wording of the questions confused them while my interview questions did not. Additionally, the students may have just lacked the verbal skills necessary to discuss their knowledge and the processes they use to gain that knowledge. Many students, even at the post-secondary level, have yet to achieve the sort of cognitive self-awareness that the think-aloud protocol may require (Gregory Schraw et al., 2006).

Despite these difficulties, characterizing students' cognition over various contexts provided useful results. It is clear that vast differences in participants' cognitive knowledge and processes exist between test scores, embedded question responses, and verbal explanations. Moreover, the modules added an extra dimension to these characterizations. Within the modules, students were given opportunities to explore microscopic environments and reference visualizations of processes that occur at the molecular level. Although I cannot say with certainty that the modules helped students transform their knowledge into meaningful, rather than rote, learning, it is clear that the modules did have some impact on my participants' knowledge of the three concepts. They referenced the visualizations that the modules provided in their free-response questions, interview responses, and drawings, using their experiences in the modules to explain how they gained knowledge. This is, however, more about a reflection of the differences between learning contexts than an endorsement of the modules.

Characterizing students' cognition over various contexts is thought provoking, but is it useful in science and education? US school systems rely on the increasingly pervasive method of standardized testing, mainly due to No Child Left Behind (Bush, 2001), which established multiple standardized test score goals that schools must meet in order to receive funding. The requirements of NCLB make it difficult for teachers to go beyond "teaching to the test" (Jerald, 2006) and, by extension, make the very idea of characterizing students' cognition in various learning contexts extremely difficult. The process is time-consuming and, while it may be fruitful, does not seem to fit with the current method of schooling. Despite this limitation, characterizing students' knowledge in different ways is a useful endeavor. Some teachers already do this in small ways—for instance, by using the Revised Bloom's Taxonomy (L. Anderson & Krathwohl, 2001). The taxonomy provides a framework for teachers to evaluate their lessons and assessments and determine whether they are asking students to respond to lessons and questions in varied and challenging ways. Using this taxonomy can provide some small insight into students' cognition over various contexts. Although it does not provide the same level of detail and insight that cognitive contextual characterization can provide, it is an adequate start.

Conclusion

In this study, I used multiple learning and assessment methods to characterize students' knowledge of molecule movement. As part of the data collection process, participants completed modules designed to elicit understanding of previously defined concepts. Despite fairly consistent test scores and forced-choice question scores within the modules, the students maintained misconceptions related to the direction of molecule movement, the impetus for molecule movement, and equilibrium. These misconceptions not only affect students' learning of these concepts, but their future understanding of other key concepts, as the concepts are important to chemical equilibrium, respiration, photosynthesis, and many other biological and chemical processes. This study illuminates key content misunderstandings. Undoubtedly, more research is necessary in order to truly evaluate the modules and their usefulness in the science classroom. Regardless of the effect of the modules, it is clear that using contextual knowledge characterization as an analytic tool can provide deeper understanding of student knowledge and cognition. A larger-scale study with more participants in different settings could further assist in piloting these individual evaluations of student cognition, as they provide a much-needed variation on assessment. Using this method, educators can assess student knowledge over multiple and varied learning contexts, illuminating key misconceptions that may have remained hidden if examined in only one context.

CHAPTER 4

METACOGNITION IN THE SECONDARY SCIENCE CLASSROOM: A COGNITIVE/METACOGNITIVE CODING MODEL FOR THE CONCURRENT THINK-ALOUD PROTOCOL

Teachers are charged with educating students and providing them with meaningful learning experiences, but what learning is considered meaningful, and on what basis can it be decided that students are sufficiently educated? Consider this statement by Kuhn and Dean (2004): "The growing reliance on standardized testing of basic skills, with higher and higher stakes, poses a grave danger to the quality of education. We need better definitions of what it means to be an educated person" (p. 273). Many researchers believe that, instead of relying on standardized testing, focusing on improved, cognition-focused educational techniques helps students to surpass surface understanding and dig deeper into their own learning processes (Garofalo & Lester Jr., 1985; Pintrich, 2002). Although there is a great deal of disagreement on how we can best increase student accomplishment of this deeper understanding, it is generally agreed upon that studying students' metacognition—their thinking about thinking—will lead us in the right direction. For instance, Georghiades (2000) made a representative statement of this sentiment when he emphasized the importance of enabling students to improve their metacognition, or in other words, to think more critically about their own thinking: "Metacognition is widely believed to make students responsible for their learning, hence more actively involved in the learning process, and there is growing literature advocating positive impact on students' achievement" (p. 126). Unfortunately, how best to encourage development of students' metacognitive knowledge and skills, how to evaluate metacognition, and even the definition of metacognition are topics of debate among education scholars (Zohar & Dori, 2012).

Through the investigation of student interactions with (both through interviews and in response to test questions) and learning from three computer-based modules covering important and often misunderstood science topics (osmosis, filtration, and diffusion), I worked toward a better understanding of these problems of metacognition within a science education context. In this attempt to deepen the pedagogical understanding of metacognition and work toward resolution of issues that arise from its complicated nature, I sought to accomplish the following: First, I aimed here to provide a background and extensive literature review of the existing research on metacognition, especially as it pertains to secondary science learning. This will provide a base for my own research and give future researchers a synthesis of current scholarship. Two, given the ambiguity of research on the methods associated with assessing metacognition, especially when using think-aloud interviews, I developed a model to code my own data for metacognitive knowledge and processes. This model can be used by other researchers to code transcripts from observations and interviews, and to further extend the scholarship of student metacognition. Third, I applied the newly created model to my data and coded it (as seen in the sample in the research section below), characterizing students' metacognition as they worked through the modules. In these ways, I hoped to add clarity to the role of metacognition in the secondary science classroom and provide a usable tool to help future educators analyze think-aloud interview exercises.

Research Questions

My initial interest in this area of research stemmed from several perceived gaps in the literature. These gaps included "fuzzy" definitions of metacognition (Veenman, 2012), inconsistencies in how metacognition has been measured in research situations (Gregory Schraw & Dennison, 1994; Vermunt, 1998), and methodological challenges related to coding student data (from interviews, in particular) for evidence of metacognitive knowledge and processes (Jacobs & Paris, 1987; Rickey & Stacy, 2000). All of these issues are important in moving the field of metacognition research forward. However, in my study, I found that not having a model with which to code student data from interviews presented the greatest difficulty. This idea will be explored in the literature review and developed in greater detail, but I must first present the research questions that I formulated to address these gaps and guide this study:

1. To what degree can a synthesis of existing scholarship be used to construct a valid model to direct the coding/analysis of student data resulting from interviews related to metacognition while those students are participating in a science learning task?
2. To what degree can analysis of student metacognition using the model described above result in thorough characterization of student metacognition?

In the sections that follow, I first provide an in-depth analysis of metacognition and the various models currently found in the literature from articles focused on metacognition that I gathered, read, and analyzed. I then explain my process in creating a model and applying it, and address the successes and challenges this model may offer other educators.

Review of the Literature

Defining Metacognition. The definition of cognition, at least as understood within the sciences, includes knowledge and processes such as attention, memory, language skills, learning, reasoning, problem solving, and decision-making (Matlin, 2009). The concept of cognition refers to understanding and interpreting the world and all of its aspects. Metacognition is a related, but distinct, concept. In a brief article that has become one of the cornerstones of educational research, J. H. Flavell (1976) defined metacognition as "one's knowledge concerning one's own cognitive processes and products or anything related to them" (p. 232). For example, when a student analyzes alternative and possibly wrong answers on a multiple-choice question to ensure that the answer she chose is correct, she is engaging in metacognition. This behavior can be labeled as metacognition because the student in this case is not only using their cognitive knowledge (i.e. knowledge of facts and concepts) but their metacognitive knowledge (i.e. knowledge of the goodness of fit between the answer choices and their own conceptions of the face/concept). Flavell theorized that a process of metacognitive self-regulation could be achieved through planning, monitoring, evaluating, and exerting some level of control over one's thoughts. An important point in this theory lies in his distinction between *metacognitive knowledge* and *metacognitive monitoring and self-regulation.* Flavell (1979) defined metacognitive knowledge as an individual's "beliefs about what factors or variables act and interact in what ways to affect the course and outcome of [one's own] cognitive enterprises" (p. 907). In other words, one example of metacognitive knowledge (as an aspect of metacognition) refers to an individual's understanding of the way they learn. Many different factors, both inside and outside of the mind, change the way that learning occurs. For example, a student's pre-conceptions of a certain topic may influence the way that topic is understood; learning could be just as easily affected by a cultural barrier between the instructor and student that results in lost meaning of key terms. He broke the understanding of these influential variables down into three categories: knowledge of people (self and others), knowledge of tasks (nature of information and nature of tasks), and knowledge of strategy (how to achieve cognitive goals) (Flavell, 1979; Schraw & Moshman, 1995). Within each of these areas, an individual has the ability to control and enhance, to a certain extent, her own thinking. The action taken to control and enhance thinking based on metacognitive knowledge was dubbed metacognitive monitoring—the second type of metacognition outlined by Flavell. This type of monitoring "consists of self-regulatory mechanisms in reading, studying, and problem solving; they are the deliberate tactics that learners engage in to insure [*sic*] success and efficiency" (R. E. Reynolds & Wade, 1986, p. 309). Thus these components of metacognition allows learners to control their cognition by allowing them to redirect how emphasis is placed on a learning task or through the dissection of a problem situation to find what components comprise the problem and which do not. Tools that help learners to evaluate their own process or progress fall into the category of metacognitive monitoring. It is achieved through the four steps outlined above: planning (selecting appropriate strategies and resources), monitoring (having a level of awareness about one's own performance), evaluating (judging a task's success and efficiency), and ultimately controlling, in which a student can adjust his or her line of thought to better develop and explain new information (Flavell, 1979).

It is important to note the distinction between metacognitive knowledge and metacognitive monitoring, as the conflation of these concepts is one of the main problems in metacognitive research (Zohar & Dori, 2012). Metacognitive knowledge and metacognitive monitoring form the basis for Flavell's definition, and as a result, are the foundation for all other research on the subject. (See figure 4.1). Any general definition or sub-category likely falls under one of these two categories, as evidenced by the progression of knowledge illustrated below. However, as new researchers grapple with these terms, the two areas of metacognitive knowledge and metacognitive monitoring have increasingly been shown to be inextricably related and connected. This relationship informs my own research and the development of a model that incorporates both areas while acknowledging their connectivity and their distinct definitions.

Two other necessarily related concepts within the field of learning research are cognition and metacognition. Similarly, the distinction between cognition and metacognition is often muddled. Flavell (1976) draws a line between cognition and metacognition by defining metacognition as a higher level of cognition that *acts* on cognition. His research presents and is based on the concept of a separate but interactive relationship, in which one's knowledge of a concept (cognition) can be shaped by the way that a person learns about, explains, and interprets his or her own learning styles (metacognition) For example, recognizing that *saludo* is the Spanish word for *greetings* is cognition. Tracing that word to its Latin roots, using the pseudo-homonym "salute" as a memory tool, or eliminating other choices in a multiple-choice situation would all be examples of metacognition. The relationship between cognition and metacognition presented by Flavell argues that metacognition can affect cognition, but that cognition can also exist independently. This belief is pervasive in later scholarship, leading to many studies in which cognition is discussed without mention of metacognition, or in which metacognition is researched independently from cognitive processes (see Zohar & Dori, 2012). That separate but interactive relationship between metacognition and cognition may also explain some of the confusion surrounding both terms.

Flavell's (1976) explication of the concept of metacognition opened up an entirely new field of scholarship and, as tends to happen with new concepts, various scholars proposed alternative versions (p. 232). Veenman (2012) wrote that, "One of the reoccurring problems with metacognition research is the 'fuzziness' of the concept and its constituents" (p. 22). As a result, he and many others have contributed their own definitions of and new components to metacognition. Since it was first presented by Flavell, the definition has changed and evolved to include new theories and new views on the subject, though all can be roughly categorized under the original categories of metacognitive knowledge and metacognitive strategy.

In their 1987 work on metacognition, Jacobs and Paris incorporated a social aspect to metacognition, defining it as "any knowledge about cognitive states or processes that can be shared between individuals" (p. 258). Thus their definition shifts away from the original Flavell definition by the addition of communication. In this case, the authors referred to knowledge about cognition that can be demonstrated in some way (i.e. communicated, examined, etc.). Later the authors use this language: "Thus, it is reportable, conscious awareness about . . . thinking" (p. 258). After defining metacognition in this way, Jacobs and Paris (1987) further divided the concept into two broad categories—self-appraisal of cognition and self-management of thinking. They explained the distinction between these terms through the definition of a series of categories and the production of specific examples. "Self-appraisal refers to the static assessment of what an individual knows about a given domain or task… these appraisals of thinking appear to fall into three broad subcategories that we refer to as declarative, procedural, and conditional knowledge" (p. 258). Unlike cognition, which refers to the knowledge itself, self-appraisal (as a form of metacognition) relates to one's own measurement of that knowledge. Again, as in Flavell's conception, cognition and metacognition are separated. For example, declarative knowledge refers to learners' assessment of their ability to explain or believe the truth of a specific fact or concept. The authors go on to further explain each level of self-appraisal:

> Declarative [metacognitive] knowledge refers to what is known in a propositional manner…Procedural [metacognitive] knowledge refers to an awareness of processes of thinking…Conditional [metacognitive] knowledge refers to an

> awareness of the conditions that influence learning such as *why* strategies are effective, *when* they should be applied and *when* they are appropriate. (p. 258)

Here, Jacobs and Paris do not merely separate metacognition into a knowledge component and a strategic component, as was done by Flavell. They focus instead on the three types of metacognitive knowledge (declarative, procedural, and conditional), or self-appraisal, which lead to and cannot be separated from metacognitive monitoring strategies such as self-management. Beyond understanding tools to improve cognition, these researchers believe metacognition to primarily concern one's own self-understanding. Whereas Flavell (1976) made a point to differentiate metacognitive knowledge from monitoring and self-regulation, these researchers further divided the categories of knowledge to include self-appraisal, and put forth the view that all metacognition is necessarily related; metacognitive knowledge, particularly self-management, both fuels and informs the process of regulated thinking. However, they still maintain the two categories of self-appraisal and self-management, which are roughly congruous to metacognition and self-monitoring—the original terms put forth by Flavell (See Figures 4.2 and 4.3).

Other scholars have taken apart the two theoretical components of metacognitive knowledge and metacognitive monitoring, further delineating them into subcategories. Kuhn (1999), for example, separated metacognitive knowledge into three categories she labels meta-knowings. In her research, she also re-purposes the term metacognitive to meet a much more limited definition within the types of knowledge. Kuhn's three categories are thus labeled as metastrategic (knowledge of strategies), metacognitive (declarative metaknowledge), and epistemological (meta-knowledge of how an individual or a group knows). She focuses on the aspects of *selecting* and *monitoring* applied strategies:

> The distinction between metastrategic and metacognitive knowing rests on a widely employed dichotomy in cognitive psychology (as well as in philosophy) between procedural knowing (knowing how) and declarative knowing (knowing that). Meta-knowing differs depending on the kind of first-order knowing that is its object. Procedural or strategic knowing entails the exercise of strategies to achieve goals, thus invoking the potential for a second-order metastrategic form of knowing that selects and monitors the strategies that are applied – a manager of the reparatory of available strategies. Metacognitive knowing operates on one's base of declarative knowledge, which also stands to benefit from executive management. What do I know, and how do I know it? Finally, epistemological knowing has to do with an individual's broader understanding of knowledge and knowing. It has both a general, philosophical aspect—How does anyone know?—and a personal aspect—What do I know about my own knowing? (p. 18).

Much of the confusion that surrounds metacognition has to do with the terminology. Within Kuhn's conception of metacognition, she explains metastrategy as "knowing how" and metacognition as "knowing that," although these two terms could be considered synonymous with Flavell's terms metacognitive strategies and metacognitive knowledge, respectively. Her model shares similarities with others—her emphasis on the personal speaks to Jacobs and Paris's (1987) focus on self-appraisal and social considerations, for example—but her division of metacognition into three categories sets her apart from those researchers. Similarly, both Flavell (1976) and Schraw et al. (2012) include "evaluation" under metacognitive monitoring, but in Flavell's case it is perceived as the step before self-monitoring and control. Schraw and his colleagues, on the other hand, equate it with "de-bugging" and connect the concept closely with information management. Each of the researchers mentioned here believed that metacognition has many contributing aspects and additional categorizations—most choose to group it into three separate subcategories. Flavell's three knowledges (people, tasks, and strategies) are congruous to the concepts of declarative, procedural, and conditional knowledge outlined by Jacobs and Paris, though there are distinctions. For example, declarative knowledge does not necessarily relate to one's ability to explain knowledge to other people. Once again, although specific terminology is used by Jacobs and Paris to refine the concept, it also clouds the issue.

Another key resource for my research was The Revised Bloom's Taxonomy (Anderson & Krathwohl, 2001). This tool characterizes educational objectives that teachers and researchers can use to assess learning objectives, and the thought processes described therein (remembering, understanding, applying, analyzing, evaluating, and creating) are necessary predecessors to metacognitive control and self-regulation. The Revised Bloom's Taxonomy is not strictly a presentation of metacognition; rather, the Taxonomy is usually used for assessments and lesson plan components. "Stated simply, when we teach, we want our students to learn. What we want them to learn as a result of our teaching are our objectives" (L. Anderson & Krathwohl, 2001, p. 3). It may seem counter-intuitive to include the *Revised Bloom's Taxonomy* in the literature about metacognition, as it is actually a cognitive taxonomy and only one category (metacognitive knowledge) explicitly mentions metacognition. However, in explaining why they included only one category explicitly mentioning metacognition, the authors wrote:

> …metacognitive control and self-regulation require the use of the cognitive processes included on the other dimension of the Taxonomy Table. Metacognitive control and self-regulation involve processes such as *Remember, Understand, Apply, Analyze, Evaluate,* and *Create*. Thus, adding metacognitive control and self-regulation processes to the

> cognitive process dimension was seen as redundant. Second, *Factual, Conceptual,* and *Procedural knowledge* as conceived in the original Taxonomy pertain to subject matter content. In contrast, *Metacognitive knowledge* is knowledge of cognition and about oneself in relation to various subject matters, either individually or collectively (e.g., all sciences, academic subjects in general) (L. Anderson & Krathwohl, 2001, p. 44).

The Revised Taxonomy is constructed as a statement of the authors' belief in a progressive overlap of the metacognitive and cognitive fields of study. The increased scholarly interest in metacognition in recent years reflects and expands upon the understanding that cognition and metacognition are inextricably connected.

Detailed Examinations of the Recent Definitions of Metacognition. The last decade has seen a marked increase in the volume of study regarding metacognition, as well as the refinement of the concept of "metacognition" as a trait of learners. The following three definitions illustrate the distinct and varied conceptualizations of the term seen in 2012 alone. The first definition of metacognition is also one of the most straightforward: "one's declarative knowledge about the interplay between person, task, and strategy characteristics" (Veenman, 2012, p. 22). In this definition, metacognition must be a form of conscious cognition that can be communicated, as was suggested by Jacobs and Paris in their 1987 study. This points to a shift from the distinct nature of metacognition and cognition touted in much of the previous literature, and is more in the direction of my own model. Veenman's definition can be linked to Flavell's definition, but Veenman adds the idea that metacognitive knowledge could be correct or incorrect. In his conceptualization, metacognitive *knowledge* implies choosing a strategy, implementing the strategy, and applying cognitive processes, which contrasts with Flavell's limited definition of strictly three categories of knowledge (people, tasks, and strategies), without the requirement of corresponding immediate action. Another example of recent scholarship on metacognition is a conception of metacognition that was stated as follows: "knowledge of thinking processes, awareness of one's own processes, the ability to control those processes, and willingness to exercise that control" (Herscovitz, Kaberman, Saar, & Dori, 2012, p. 167). In their model, knowledge of thinking processes is exemplified when one considers and decides among different strategic routes in choosing how to proceed within a problem-solving situation. If a problem situation is set up in which the learner is challenged with moving from point A to point B by his/her choice of three different routes, then the metacognitive aspects of this task involve evaluating and comparing the advantages, risks, and rewards inherent in taking any of the three routes.

A third, more succinct, definition of the term is "demonstrating awareness and understanding of one's own cognition" (Schraw, Olafson, Weibel, & Sewing, 2012, p. 58). Demonstrating awareness and understanding can be interpreted as being conscious of the range of choices available to you, evaluating them, possibly comparing them, and making a choice about how to proceed based on a rationale founded in the analysis of that information. In addition, Schraw et al. (2012) included a model that links metacognition with two new terms: metamemory (which includes components of memory strategies and judgments of learning) and metacomprehension, which they viewed as a concept that encompassed both metacognition and metamemory (see Figure 4.1). Metamemory is the ability to be aware of one's own memory capabilities, while metacomprehension refers to the broadest level of comprehension available, which leads directly to the ability to self-regulate. Clearly, all of these authors have expanded upon Flavell's (1979) original conception by adding their own subcategories and qualifications, yet all still maintain the two main components: metacognitive knowledge and metacognitive monitoring (Figures 4.2 and 4.3). For a different visualization of the components of metacognition separated by author, see Table 4.1. Ultimately, what these various definitions hold in common is the conceptualization of metacognition as both a form of knowledge that exists at a higher level than normal declarative or procedural knowledge and as a means for monitoring one's knowledge. The existence of these two aspects of metacognition allow for the evaluation and implementation of knowledge and monitoring, in which knowledge of one's learning processes and control of one's thoughts combine to deepen understanding.

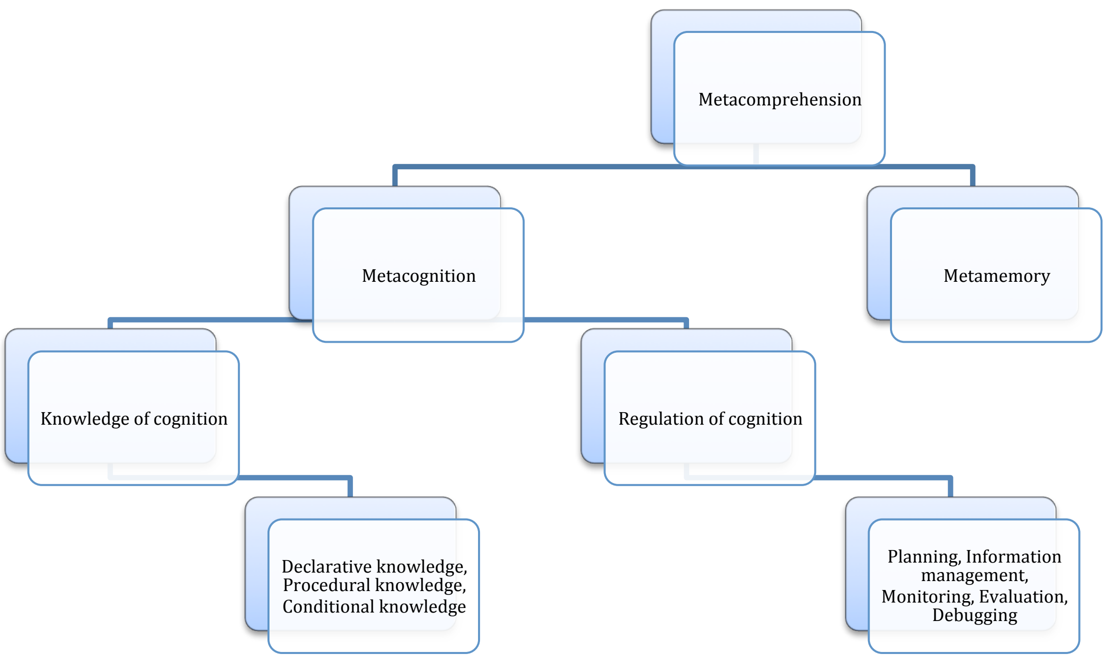


Figure 4.1. Adapted from Schraw et al. (2012): Relationship between metacomprehension, metacognition, and metamemory.

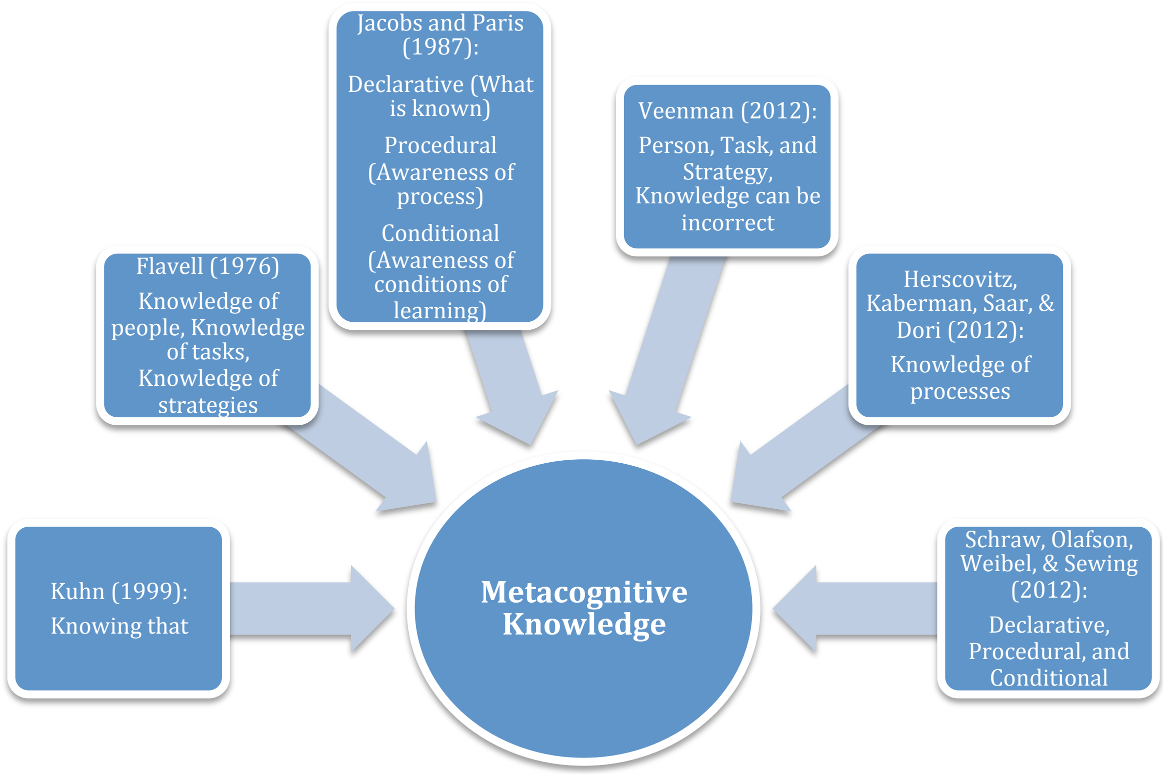


Figure 4.2. Components of Metacognitive Knowledge by Author.

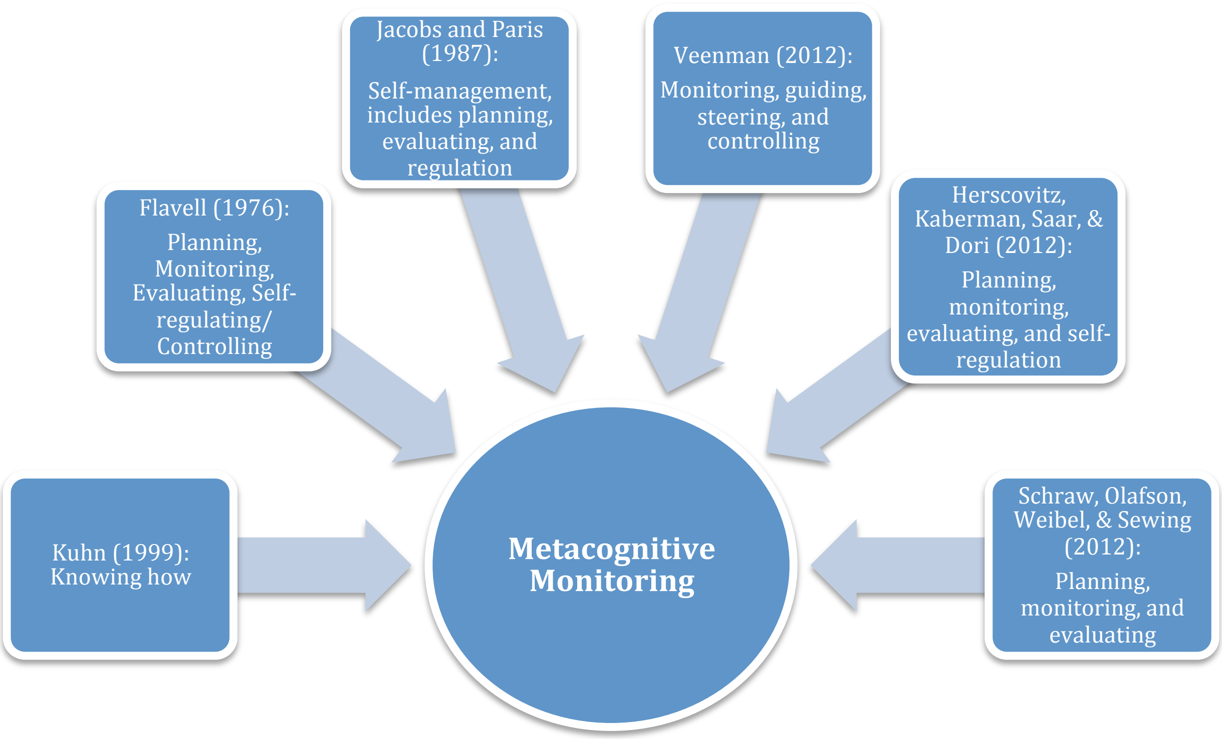


Figure 4.3. Components of Metacognitive Monitoring by Author.

Table 4.1
Components of Metacognition by Author(s)

Author	Metacognitive Knowledge			Metacognitive Monitoring			
Flavell (1976)	Knowledge of People	Knowledge of Tasks	Knowledge of Strategy	Planning	Monitoring	Evaluating	Self-regulating/ Controlling
Jacobs and Paris (1987)	Declarative: What is known	Procedural: Awareness of process	Conditional: Awareness of conditions of learning	+		+	+
Kuhn (1999)	Metacognitive: Knowing That			Metastrategic: Knowing How			
Veenman (2012)	+	+	+	+	+	+	+
Herscovitz, Kaberman, Saar, & Dori (2012)			+	+	+	+	+
Schraw, Olafson, Weibel, & Sewing (2012)	Declarative	Procedural	Conditional	+	+	Evaluation/ Debugging	Information Management

+ indicates that the component is represented in the author or authors' work

Metacognition and Learning. Based on the preceding scholarship and research, metacognition can justifiably be defined within the literature as a learner's conception of one's own learning processes, which is the first step toward controlling and optimizing these processes. Defining metacognition is an important beginning to improve teaching methods through its application. To understand how we can best use metacognition to explain how students learn, we must also have a good definition of learning—and an understanding of the relationship between the two concepts. Learning is "provoked by situations . . . by a teacher, with respect to some didactic point; or by an external situation. It is provoked, in general, as opposed to spontaneous" (Piaget, 1997, p. 20). In other words, as teachers, we direct learning, instigating the process for students. Mayer (2002) wrote that teachers must also work to drive a specific kind of learning. It is easy to see the link between metacognition as defined by the various scholars mentioned above and Mayer's definition of meaningful learning within the context of problem solving. Mayer believed that there exist two types of learning, rote and meaningful, and suggested that we should be attempting to provoke the latter.

> Meaningful learning occurs when students build the knowledge and cognitive processes needed for successful problem solving. Problem solving involves devising a way of achieving a goal that one has never previously achieved . . . Two major components in problem solving are (a) problem representation, in which a student builds a mental representation of the problem, and (b) problem solution, in which a student devises and carries out a plan for solving the problem. (Mayer, 2002, p. 227)

Although Mayer characterized the problem-solving process as cognitive, I argue that it also has metacognitive components. For instance, Zohar's (2012) writings on metastrategic knowledge, or knowledge of metacognitive strategies, tie into Mayer's (2002) concept of problem solution.

Remembering methods that worked in the past and applying them (metastrategy) is one way that students can create a problem-solving plan. Teachers can also inspire meaningful learning, as opposed to rote memorization, by working to develop metacognitive awareness early in the educational process (both with young students and at the beginning of a unit, for example), through tools such as on-line interviewing (think-aloud interviews), that encourage students to verbalize their thought processes (Van Someren et al., 1994; Veenman, 2012). These types of tools lead to a verbalization that addresses Mayer's (2002) theory of problem representation and problem solution. Some scholars theorize that promoting metacognitive instruction in the classroom from a young age will lead to a deeper understanding of the material being taught, including longer "durability" of the content (long-term memory) and more successful transfer skills (applying knowledge to other concept areas) (Georghiades, 2000). Although most of this research concerns K-12 students' metacognition, understanding and implementation of metacognitive instruction presents a challenge that is not limited to K-12 schooling. Even at the post-secondary level, many students fail to use metacognition (Gregory Schraw et al., 2006). Teachers can address this problem by working to begin metacognitive awareness early in the educational process, for example, by asking kindergartners what they are working on or how they chose an answer.

However, developing students' metacognitive knowledge and skills at any level is an undertaking that is complicated and not well understood. Kuhn and Dean Jr. (2004) wrote that one way of supporting this metacognitive development is by having students "reflect on and evaluate their activities," and that doing so "should heighten interest in the purpose of these activities" (p. 270). Reflecting on lessons and activities can be as simple as having students write out their ideas and impressions:

> The act of writing is assumed to be a goal-directed thinking process in which the writer engages in four kinds of mental processes. These mental processes are planning, translating ideas and images into words, reviewing what has been written, and monitoring the entire process. There is considerable interactivity between the four processes so that the act of writing is recursive rather than linear. (W. M. Reynolds, Miller, & Weiner, 2003, p. 89)

In fact, some science educators believe that "reflection is the most important cognitive mechanism for promoting critical thinking and metacognition" (Schraw et al., 2006, p. 124), as critical reflection provides students with opportunities to move beyond a teacher's explanation of a subject, think differently, and create their own understanding of both the subject and the learning process. Of course, self-regulated learning helps to develop numerous processes. Jacobs and Paris argued that self-regulation is also tied to planning, evaluation, and regulation—all traits and processes that lead to improved metacognition and increased knowledge (Jacobs & Paris, 1987, p. 259). For example, students can change their study strategy based on the material that they are studying; chemistry material may become clearer from practical examples, while history can be studied through extensive reading and the examination of contemporary documents to create a context. They can also evaluate their own learning by pausing, paraphrasing, and asking themselves questions about the content. By using self-regulated learning, students not only work to develop their own knowledge and cognitive processes, but also develop metacognitive knowledge and shape metacognitive processes. Additionally, self-regulated learning has students "contribute actively to their learning goals and exercise control of goal attainment," rather than being passive participants in the learning process (Reynolds et al., 2003, p. 59). As a result, the learning that takes place is both more meaningful and more permanent, making this a critical skill for teachers to share with students at all levels and in all subjects.

Metacognition and Science. The creation of my model had the intention of serving science educators and researchers on science education, in particular. Though the model can be applied in other contexts, as further explained in the discussion, it depends on and builds from a necessary connection between metacognition and learning science. Specific attributes of science learning (such as the troublesome nature of "invisible" processes that happen on a molecular level, like those illustrated in the module) inform this research and justify the need for both a visual simulation and the development of metacognitive skills in science students.

Science, in particular, can benefit from specific curricula aimed at developing students' metacognitive knowledge and skills. This is especially true within the areas of learning application, visualization, and reading skills. Science "draws on many different cognitive processes, such as those involved in reading text, problem-solving, inquiry learning, and writing" (Veenman, 2012, p. 28). While language students may be able to isolate their knowledge (for example, an extended vocabulary does not necessarily equate to or affect a solid understanding of grammar), science requires students to pull together various learning tools and strategies to grasp complicated concepts, such as osmosis and filtration, which cannot be experienced first-hand. Since metacognition can help deepen students' understanding of concepts, extend their long-term memory, and increase their ability to transfer knowledge and skills to other topics, it is especially useful in this area of education (Georghiades, 2000).

Metacognition also plays an important role in visualization; according to Gilbert, "having failed to develop . . . metavisual competence will have serious consequences" (2005, p. 18). By this statement, Gilbert alludes to the fact that some of the content in science, especially in chemistry and physics, is invisible to the naked eye and thus difficult to demonstrate directly in the classroom. There are processes that occur either at the micro or macro level, too small or large to see, or concepts that cannot be seen and must, instead, be modeled to the best of our abilities. For instance, the evolution occurs gradually over many years. Within a student's lifetime, he or she is unlikely to directly observe it in action, though evidence certainly exists of its effects. As such, the process itself must be modeled using growth models or other strategies. Science students depend on the ability to visualize; many concepts initially appear abstract and invisible (such as dialysis) but require a fully concrete solution and understanding.

Finally, metacognitive skill has also been shown to have impact on students' reading skills, a major component of science that requires students to take in a great deal of information both in the classroom and at home through textbook study (O'Reilly & McNamara, 2007). This is especially important, since having well-developed metacognitive knowledge and skills could, potentially, help students compensate for deficiencies in science knowledge. In this way, the development of metacognitive skills in students grants the ability to improve other, fundamental skills that can be useful in science learning and applied across other disciplines.

These kinds of skills—critical reading, visualization, big-picture thinking—are critical for student advancement, but teachers, due to lack of understanding, are not able to help students attain them. "Although the benefits of metacognition on learning are clear, metacognitive strategies are not being used in the classrooms as they should be" (O'Reilly & McNamara, 2007, p. 187). Science education would benefit from an increased emphasis on metacognitive skills, beginning with a thorough definition of these skills and an understanding of the importance of their application, as outlined here. From there, teachers may be able to detect and classify metacognition, eventually gaining the ability to fully code it for further analysis.

Methods

In my attempt to fill the knowledge gap on metacognition and assist other educators in examining and encouraging metacognitive thought in the classroom, I chose to implement think-aloud interviews as a data-collection tool, primarily because it occurs during learning, as opposed to after. Most attempts to measure metacognitive knowledge consist of self-reporting methods, such as questionnaires, evaluations, or interviews (Veenman, 2012). In his work on metacognition, Veenman attempts to measure metacognitive skills in two categories: on-line (during the task) and off-line (after the task). There is a key distinction between these two methods. Off-line measurement relies on self-report, much like attempts to measure metacognitive knowledge, as the task has finished (i.e. a survey). On-line measurements, however, are obtained from judges "external to the learning process" during the learning process (2012, p. 28). Those researchers who focus on quantitatively characterizing metacognition most commonly use questionnaires, evaluations, or surveys (eg, Schraw et al., 2012; Schraw & Dennison, 1994). Scholars who avoid these methods in favor of a more qualitative assessment of student learning usually focus on on-line interviewing, often called concurrent think-aloud interviews.

Think-aloud interviews entail a student, a participant, and a learning exercise of some sort They usually involve the researcher recording participants as they talk through their thought processes while problem solving or answering test questions based on newly acquired knowledge (Van Someren et al., 1994). An early use of this form of data collection can be seen in cognitive psychology; it was first used to explore the thought process of expert chess players (Kelley & Capobianco, 2012). One of the advantages of think-aloud interviews is that researchers can record both cognition and metacognition by coding the various answers given by participants for their association with these traits (Ericsson & Simon, 1993). For example, a student may demonstrate their understanding of a concept (cognition) by providing a correct answer, while simultaneously giving clues to metacognitive strategies by verbally eliminating wrong answers. Additionally, think-aloud interviews allow participants to use their own language in their descriptions, and provide a more natural and less stressful approach to interviewing, which is especially helpful when the participants are younger children (Ericsson & Simon, 1993; van Someren et al., 1994). A relaxed student is likely to give more answers, and to be more forthcoming about frustrations or skills. Furthermore, though the think-aloud protocol is certainly useful for recording individual students' metacognition, it can also be used in the classroom as a tool to *promote* metacognition. Joseph applied this advantage specifically to reading exercises: "Using this think-aloud technique, teachers can demystify the reading process by explaining the behind-the-scenes thinking required for good comprehension" (2010, p. 101). However, it is clear that this method could be very useful in science, where reading is a large part of the curriculum.

Although think-aloud interviews can be extremely useful, they can also be difficult to implement. This method of interviewing presents two significant challenges to educational researchers. First, K-12 students often have trouble verbalizing their thoughts, which can make explanations difficult to understand (Bowen, 1994). Second, and perhaps more importantly, there is very little information detailing how to code (i.e. create categories defined within the data) for metacognition on think-aloud protocol transcripts. With such an ambiguous topic as metacognition, it is imperative that researchers decide how metacognition can be coded for in students' language. I have found very little evidence in the literature of specific models that researchers can use to code metacognitive knowledge and processes. In the only article I have found that specifies a coding method, Kelley and Capobianco (2012) identified seventeen total codes that emerged during the concurrent think-aloud protocol sessions: analyzing, computing, defining problems, designing, interpreting data, modeling, predicting, questions/hypotheses, and testing, among others. Although specific, the codes are not categorized as being cognitive, metacognitive, knowledge-based, or process-based. While other articles discuss the proper utilization of the concurrent think-aloud protocol (i.e. Bowen, 1994; Nielsen, Clemmensen, & Yssing, 2002), I have not found any other research that provides a specific model scholars can use to code the resulting transcripts from this method of data collection.

A Coding Model for Metacognition

Having a model that researchers can use to code for metacognition is significantly useful for two reasons—first, a model like this is absent in the literature. As stated above, very few scholars delve into the process they use to code for metacognition when using think-aloud protocols, and those who do, such as Kelley and Capobianco, choose not to categorize their codes in terms of cognition or metacognition (2012). I feel this methodological absence hinders the field and instructors' understanding of the differences between cognition and metacognition. Studies in which researchers do provide examples of their coding methodology are limited, and usually only list some example codes, rather than the entire coding scheme. Second, a study implementing a successful metacognition coding model provides a much-needed baseline for structural educational changes and future research. As discussed, how metacognition is defined, measured, and best used in the classroom are still topics under debate. A model that, line-by-line, examines and explains student thought processes can help to both clear up some of the ambiguity surrounding metacognition, as well as sharpen the language used to characterize metacognition.

In order to create a model that could serve this purpose, I had to evaluate the relationship between cognition and metacognition. In his definition of cognition and metacognition, which would go on to shape all the research that followed, Flavell (1976) implied a separate but relational connection between the two constructs (Figure 4.4):

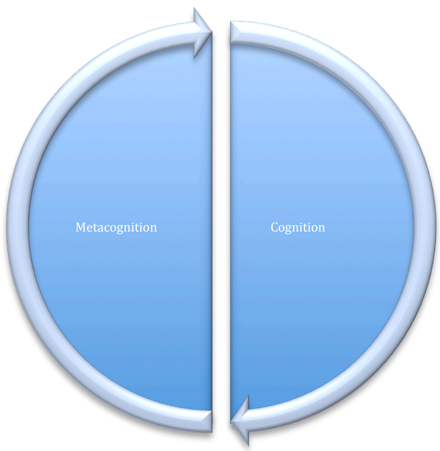


Figure 4.4. Traditional View of the Relationship Between Cognition and Metacognition.

In this model, the two concepts are connected, but can also exist separately from one another. For instance, a multiple-choice assessment question will directly demonstrate a student's cognitive skills (i.e., remembering) in a binary sense, but not any metacognitive skills, such as self-monitoring or evaluating, although these were almost certainly used in finding the answer. The process is considered separately from the result. That conception of cognition and metacognition is commonly found in Flavell's original definitions, and is repeated throughout current literature, with the exception of recent scholarship within the last two years trending toward a more connected relationship. The model I developed follows the path of these trends as a slight modification to the traditional way of thinking (Figure 4.5):

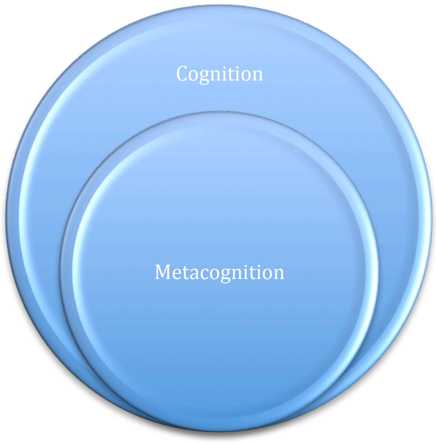


Figure 4.5. Modified View of the Relationship Between Cognition and Metacognition.

The model above paints a different picture of these two constructs. Cognition encircles metacognition and, therefore, metacognition exists within a cognitive framework. Metacognition is an integral aspect of all cognition. My model allows for the small possibility of strict cognition without the influence of metacognition, as seen in the rote learning (mere memorization without deeper knowledge) referred to by Mayer (2002), but more realistically incorporates aspects of both into each level of coding. As Schoenfield (1983) wrote, "…purely cognitive behavior is extremely rare, and that what is often taken for pure cognition is actually shaped—if not distorted—by a variety of factors" (p. 330). One of the factors that influences cognition is often metacognition, so very few scholars specifically argue that the processes can be completely separate from each other. Rather, as metacognition cannot be fully observed, it must be assumed that it may constantly be affecting cognitive processes. Referring back to the example of a multiple-choice question on an examination, it is impossible to know when and which metacognitive skills are being applied in a traditional assessment situation. This corresponds with my view that metacognition is an integral element of cognition, and not a supplementary tool.

This view, which serves as the first level of the model I have created, is supported by the literature in this field. Though Flavell proposed a comparatively isolated conceptualization of cognition and metacognition, recent scholarship acknowledges the interflowing relationship inherent between the two. For example, Rickey and Stacy (2000) wrote that “Cognition rarely occurs in the complete absence of metacognition” (p. 915). Understanding the connectivity in the relationship between cognition and metacognition was important in my development of a coding model for metacognition for the concurrent think-aloud protocol. Initially, I viewed cognition and metacognition separately when evaluating and analyzing the data. This over-simplification clouded my ability to correctly code for metacognition, as it was very difficult to distinguish cognitive knowledge and processes from metacognitive knowledge and processes. In answer to this problem, I turned to the literature and adapted a more referential and interconnected view of metacognition and cognition. Using the model in Figure 4.5, I began to view the two concepts as both interrelated and influential of each other.

Thus the connection between cognition and metacognition, as observed in my research and referenced in the literature, forms the first level of the new model I created. In addition to this perspective on cognition and metacognition, I next incorporated Anderson and Krathwohl’s (2001) Revised Bloom’s Taxonomy into the model. These researchers also claim that metacognition and cognition have a significant degree of overlap, a theory that fits well with the development of my model. Metacognition is threaded throughout the Taxonomy as a result of this belief, as evidenced through the use of terms such as “evaluating,” which speak to students’ ability to defend and explain their beliefs, indicating a deeper level of knowledge and the use of both the declarative knowledge referenced by Schraw et al. (2012). The term “evaluating” has also been used by Flavell (1976) as an example of a tool in metacognitive monitoring (see literature review above). Although it is only named outright in one category, metacognition plays a role in each of the six levels of the Taxonomy, with the possible exception of remembering—the rare instance of rote learning and strict cognition.

The Revised Bloom's Taxonomy, an instructor-centered tool, can be used both before and after learning has taken place. Although not common, I decided to use the Taxonomy to categorize learning as it occurred, rather than before or after it has occurred. Through this method I was able to better characterize metacognitive knowledge and processes, as opposed to simply cognitive expectations or results. Additionally, I felt that the Taxonomy helped me to characterize more of the *processes* associated with metacognition. Think-aloud interviews are one way to make a measurement of latent student thought processes and strategies, traits that are challenging to observe. Their use is recommended by Ericsson & Simon (1993) as a way to code thought processes for cognition and metacognition. Although I was interested in understanding the participants' metacognitive knowledge, I felt that it alone would not be sufficient, as "metacognitive knowledge categories refer only to knowledge of cognitive strategies, not the actual use of those strategies" (Pintrich, 2002, p. 220). Characterizing the specific processes that students used *as the students used them* would help me understand how metacognition relates to cognition, and how the modules provoke both cognitive and metacognitive responses.

By combining elements of previous models (a related conceptualization of cognition and metacognition and the six items within the Revised Bloom's taxonomy), as well as incorporating some of my own elements (the two broad terms of metacognitive knowledge and metacognitive strategies which I feel each theory in the literature can be categorized under), I created a model that researchers can use to code transcripts for students' metacognitive knowledge and processes. Ultimately, using this newly created model, I provide a coded subset of participants' transcripts from a previous study (Raven, 2013) to evaluate its successes and potential applications in pedagogical research. Incorporating the ideas discussed above (L. Anderson & Krathwohl, 2001; Jacobs & Paris, 1987; Kuhn, 1999; Rickey & Stacy, 2000), I created a model of cognition and metacognition that future researchers can use when coding think-aloud protocol transcripts for metacognitive knowledge and processes (Figure 4.6).

This model will be useful for several reasons. First, having a common model of cognition and metacognition that relates the two concepts assists scholars in demystifying the two concepts, which can be confusing if viewed as autonomous. Future researchers may not have to devote time to redefining the relationship between metacognition and cognition; a view that allows for any instance of metacognition to be inextricably related to cognition allows researchers to move directly into analyzing their data from that standpoint, particularly under the view that cognition rarely exists without some form of metacognition (Zohar, 2012). As a result, both are considered valid terms within a given study. Second, as previously discussed, there is not currently a model that provides a method for coding concurrent think-aloud protocol transcripts, which is one of the most common ways of recording students' metacognitive knowledge and processes. This model provides that method's effectiveness and can assist researchers in finding metacognition. For instance, when a student is explaining a concept, researchers can use the model to probe further, asking students *how* they know the concept, as in Kuhn's 1999 discussion of metacognition, whether they feel confident in that knowledge, or even if there is a metacognitive component to their cognitive knowledge, such as a strategy or self-evaluation taking place. Third, this model can bridge the gap between theory and practice. Cognition and metacognition, while heavily studied, are more often talked about in theoretical terms, such as in the creation of new categorizations, than applied as a classroom tool, as in

Blooms Revised Taxonomy, for example. Metacognition does not currently rank high in most science educators' core assessments; in fact, many teachers may not know how metacognitive skills can best be assessed. Should they use this model, researchers would be able to navigate the practical work of assessing students' cognition and metacognition, but still rely on theory to validate their conclusions.

Having framed the theoretical basis of this model, I will next proceed to a detailed description of the model's elements and their visual representation. The model I have created has three main components. The two large circles represent cognition (the larger circle) and metacognition (the smaller circle nested within). This piece of the model is built off the conceptualization discussed in Figure 4.5. The next component is a line splitting the two circles down the middle, separating both cognition and metacognition into two pieces each: a knowledge side and a monitoring side, in conjunction with Jacobs and Paris' (1987) belief that metacognition should be divided into two categories: declarative and procedural. This is also supported by Kuhn's (1999) theory emphasizing the same division. In terms of metacognition, knowledge is normally characterized under study skills (for example, "I need to re-read this section, because I'm not sure this is correct.") I chose to categorize it under the self-assessment aspect (i.e., "Do I know this? I do know this"), primarily due to the belief that metacognition is an unavoidable result of cognition. Thus, though this piece would theoretically be completely cognitive if students did not assess their own knowledge, in my research I have not found that this is case. Think-aloud interviews revealed significant questioning and evaluation, further cementing my choice to group knowledge with self-assessment as an important category of cognition and metacognition.

The monitoring side concerns applicable skills. This is the explanatory aspect of cognition/metacognition (i.e., student conceptions of the *reason* they know this information). Certain key aspects—knowledge and strategies—are found in both cognition and metacognition, a fact that is alluded to and applied in my model design. For example, cognitive knowledge entails knowing a fact, while metacognitive knowledge is being able to complete the task at hand. This third component is the application of the Revised Bloom's Taxonomy (L. Anderson & Krathwohl, 2001), separated into categories of knowledge and processes. I placed the knowledge section of the Taxonomy under the knowledge side of the model, and the processes section under the monitoring side.

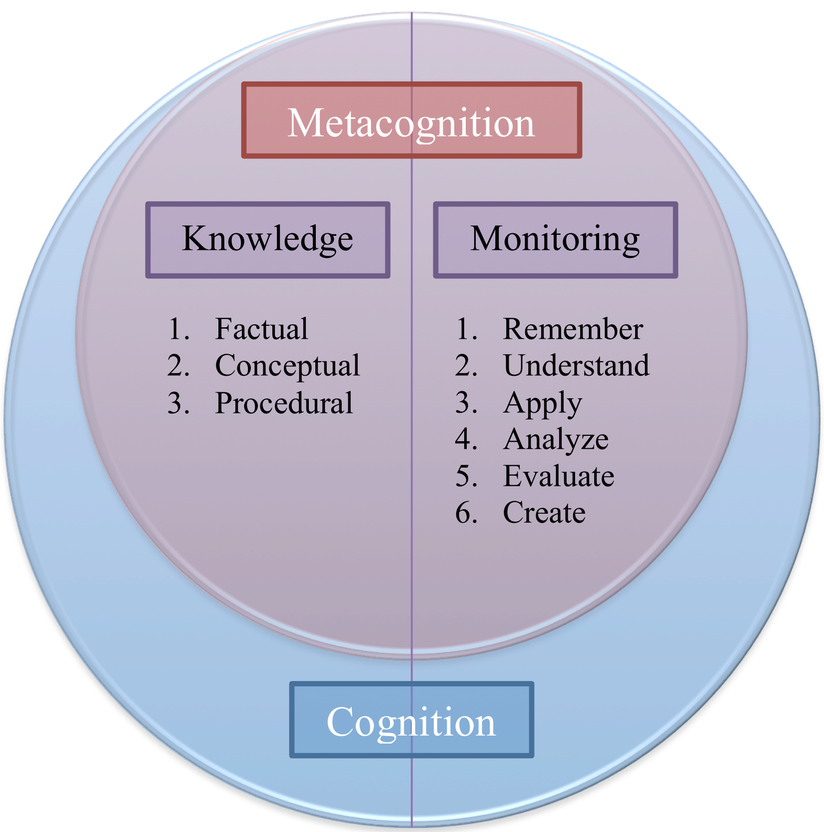


Figure 4.6. Cognitive/Metacognitive Coding (CMC) Model for Concurrent Think-Aloud Protocol Transcripts.

A second version of this model has also been provided below. This version is intended to show the dynamic aspects of the model. Additionally, in order to eliminate any confusion about the model shown above, cognition and metacognition have been split into two circles. This has been done in order to show that the knowledge and monitoring aspects, as well as the types of knowledge and monitoring shown on each side of the circle in the original model are part of both cognition and metacognition.

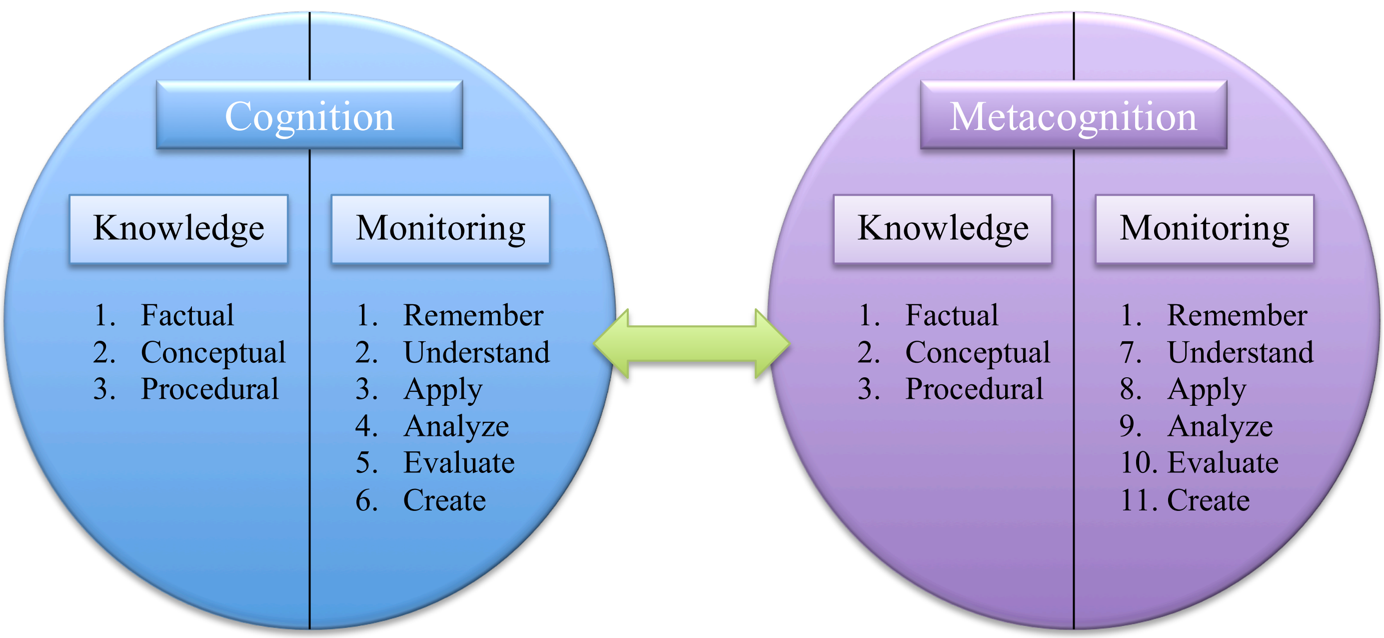


Figure 4.7. Cognitive/Metacognitive Coding (CMC) Model for Concurrent Think-Aloud Protocol Transcripts, Version 2.

Coding Data Using the CMC Model

Though simply writing down their thoughts can be effective, technology also plays an important role in student self-regulation. Some technology allows students to regulate their own learning, such as the modules in this study (Raven, 2013), which help to support additional instructional strategies. The technology in this study "supports self-regulation by functioning as: a knowledge representation tool, a cognitive scaffold, a feedback engine, and a collaborative communication device." (Gregory Schraw et al., 2006, pp. 126–127). Using the components in this model, researchers can code concurrent think-aloud protocol transcripts for cognition and metacognition. I have included a key for the coding model in Appendix F. The table displays the three levels of the coding model, descriptions for each component, and an example for each code. In order to illustrate how the coding model might work, I have chosen a subset of data from the study that provided the impetus for this research (Raven, 2013). I chose to use data from 15-year old Kendra, a ninth-grade gifted biology student. During the think-aloud interviews, Kendra was very engaged and willing to talk through her thought processes. I coded a short excerpt from her think-aloud interview from the first module (Table 4.2). Although this is a very limited selection of data, the amount of detail that the coding model provides is clearly evident. At first glance, Kendra's explanation may not have seemed overly complicated or difficult to separate into cognitive versus metacognitive knowledge and processes. However, when broken down, this 35-line selection exhibits thirteen separate codes, eight of which are unique. Breaking down Kendra's thoughts into small lines, either sentences or even individual phrases, helped code the data, since students often use multiple levels of knowledge and processes in one answer.

Taken line-by-line, the coding method becomes very easy to understand. In the section of the interview transcript coded below, student participant Kendra is exploring the concept of diffusion through the example of a cow that has been experiencing seizures. In this activity, which is an educational video game, students act as a veterinarian treating a calf with cerebral edema. Clark, the calf, has ingested too much water and lowered his blood sodium level. Choosing from three treatment options (a hypertonic, hypotonic, or isotonic solution), the students work through Clark's treatment, taking various measurements within Clark's brain to assess his progress. Throughout the game, students are presented with information about osmosis, concentration gradients, and equilibrium. In this section of data I have selected, she is evaluating the movement of free water molecules. The lesson is intended to teach her that the free water molecules will move from an area of high concentration to an area of less concentration. In the interest of keeping student responses as open-ended and unaffected by researcher presence as possible, interview questions were extremely limited in nature, generally no more than prompts such as, "What are you thinking?" In this way, students were able to reflect freely and the resulting transcript could be coded based on their own thought processes.

Consider the first code in the table: "I'm thinking of like why… like I'm picturing the visual of the free water molecules surrounding the sodium molecules" (Kendra, I1, lines 8-9). Since she was thinking about her own knowledge of a concept, I take this is evidence of metacognition in the category of knowledge as related to a specific concept. Accordingly, I coded the data MK2 (Metacognition, knowledge, conceptual). Kendra continued this thought by saying: "I'm trying to figure out why would they, why they did that. So I'm trying to put it into words…" (Kendra, I1, lines 10-11). In this case, Kendra was questioning why a process happened and how she knew that. I took that line of questioning as further evidence of metacognition, more specifically monitoring ("how do I know this?") and understanding (the ability to think deeply and evaluate a fact instead of accepting it at face value through rote learning), so I coded these lines as MM2 (Metacognition, monitoring, understand). Next, Kendra said: "Because, like, it was called dissolving when the water molecules would go take it away," continued with "but I know the sodium molecules were like attached together, and the water molecules were attached to the sodium molecules" and finished by saying "I'm trying to figure out the word for that." (Kendra, I1, lines 15-16,17-18,19). The first two lines showed Kendra's cognitive understanding of factual knowledge (coded CK1); the second two lines also showed Kendra's understanding, but of conceptual knowledge (coded CK2); and the fifth line showed Kendra's metacognition as she questioned her own cognitive knowledge (coded MK1).

Moving on to the next section of the transcript, Kendra began by relating this content to other areas of science, saying "I'm also thinking of like, since the sodium molecules were charged and so were the water molecules, they're polar?" (Kendra, I1, lines 20-21). In this case, Kendra was talking about her knowledge of a concept, coded CK2. She continued by saying, "So I was thinking they're attracted to it because it's a polar molecule so they want to have the charge zero, but I don't know if I want to put that down or not. —long pause" (Kendra, I1, lines 22-25). I used two codes in this section, as Kendra used metacognition to question her conceptual knowledge, coded MK2, then metacognitive processes to question whether she should use a certain cognitive procedure (writing something down), coded MM2. Ultimately, she decided to write that information down, stating: "I won't hurt those too much, I'll just put that down. —long pause" (Kendra, I1, line 26). I coded this statement as MM5, since she evaluated her cognitive thought processes. When I asked Kendra whether she had learned about polar molecules in biology, she said: "No it was chemistry. I'm degrading it but I'm not sure if it's right or not, so. —long pause" (Kendra, lines 28-29). Kendra again evaluated her cognitive thought processes, evidencing metacognition and monitoring (MM5). As Kendra moved on, I asked how the questions she had been answering were related to each other. She said: "Because it's saying why the free water are diffusing and it's also saying there's like, a mini-diffuse that goes like, from well, I guess from, the flow goes from high concentration to low concentration." Her answer shows two different cognitive processes, understand and analyze, coded CM2 and CM4. She concluded by saying, "So this is where the pressure on either side because more water molecules are going into the matrix than there are in the blood vessel." In this statement, she illustrated her cognitive knowledge of the principle of osmosis (coded CK2). Most of her spoken thoughts in this brief example (under five minutes of interview time) allowed for the application of at least one code, meaning that this information not only gave the researcher substantive insight into Kendra's cognitive knowledge and self-monitoring, but gives future researchers a glimpse into a potential tool by which to evaluate both student progress and teaching technique effectiveness.

Table 4.2
Coding Think-Aloud Interviews Using the CMC Model

Lines	Transcript Excerpt	Code
2 to 3	I: So what is this question asking you to find?	-
4 to 5	K: It's asking me why are the water molecules moving out of the cell instead of going into.	-
6 to 7	I: Alright.—long pause—I know it's difficult to type and talk at the same time, but what are you thinking about?	-
8 to 9	K: I'm thinking of like why… like I'm picturing the visual of the free water molecules surrounding the sodium molecules.	MK2
10 to 11	K: I'm trying to figure out why would they, why they did that. So I'm trying to put it into words…	MM2
15 to 16	K: Because, like, it was called dissolving when the water molecules would go take it away	CK1
17 to 18	K: but I know the sodium molecules were like attached together, and the water molecules were attached to the sodium molecules.	CK2

19	K: I'm trying to figure out the word for that. —long pause—	MK1
20 to 21	K: I'm also thinking of like, since the sodium molecules were charged and so were the water molecules, they're polar?	CK2
22 to 25	K: So I was thinking they're attracted to it because it's a polar molecule so they want to have the charge zero, but I don't know if I want to put that down or not. —long pause	MK2, MM2
26	K: I won't hurt those too much, I'll just put that down. —long pause	MM5
27	I: So did you learn about that concept in biology?	-
28 to 29	K: No it was chemistry. I'm degrading it but I'm not sure if it's right or not, so. —long pause.	MM5
30	I: So how do those two questions relate to each other?	-
31 to 34	K: Because it's saying why the free water are diffusing and it's also saying there's like, a mini-diffuse that goes like, from well, I guess from, the flow goes from high concentration to low concentration.	CM2, CM4
35 to 37	K: So this is where the pressure on either side because more water molecules are going into the matrix than there are in the blood vessel.	CK2

Conclusion

In this paper, I have provided a broad overview of metacognition, focusing on its various definitions, how metacognition relates to learning and science, and the multiple ways metacognition can be evaluated. Since Flavell's (1976) original introduction of the concept of metacognition, researchers have added to and amended the theoretical conception of how cognition happens at a higher level than acquisition of knowledge. Though it has generally been conceptualized within two main categories, metacognitive knowledge and metacognitive monitoring, a variety of terminology and disagreement on the relative overlap between the two has blurred the lines between these concepts. Each idea has been the subject of several articles or studies over the last thirty years. However, examining the research in this field exposed a methodological gap. Most of the research was theoretical, indicating a need for practical implementation. This implementation could, in my view, most easily be achieved through evaluating a data set concerning individual student subjects and their thought processes. One effective way of looking at student thought processes is to evaluate thinking during an assessment, as opposed to before and after, thus avoiding reliance on student memory of their thoughts or clouding effects from pre-conceived biases or misconceptions. The best tool for this purpose is a think-aloud interview. Unfortunately, when using this tool, researchers have no reliable way to code the data for metacognition. Using multiple authors' work as a base (L. Anderson & Krathwohl, 2001; Jacobs & Paris, 1987; Kuhn, 1999; Rickey & Stacy, 2000), I thus created a comprehensive model that future researchers will be able to use to code transcripts for both cognition and metacognition. I have included the categories of Bloom's Revised Taxonomy as an effective way to evaluate both cognitive and metacognitive learning. This tool could be applied in individual assessments to determine and solve student learning issues, or on a broad classroom scale to evaluate instructional effectiveness in teaching metacognition, in addition to cognitive skills.

Though the model was able to effectively code interview transcripts from this research, it may have limitations in other applications. The amount of data presented in this analysis was fairly limited, and coding a larger section of data may make coding more difficult and require a more substantial investment of time. Additionally, there are lines presented in the table above that lack codes, indicating that the model may not be as thorough as it potentially could be. Finally, this model is contingent on the researcher having a full knowledge of each of the definitions of the terms within the model, as coding data with limited knowledge would be difficult and could, potentially, lead to incomplete results.

Although the model I have proposed is a three-tiered system, using only the top two tiers (metacognition/cognition and knowledge/monitoring) in coding could also yield fruitful analytic results by helping educators better distinguish between the types of learning and the modes of expression. Once the researcher has finished coding the transcript, she can use the codes to make generalizations about students' learning processes or quantify the data. The three-tiered version of the model can then be used to further delineate the data. For example, an abundance of codes within one side of the model may indicate a need to supplement learning within the categories on the other side. As a result, students will be better equipped to drive their own future learning through a more complete understanding of their own thought processes. Overall, the model I have proposed fills an absence in the literature that is necessary for clearing up some of the ambiguity that surrounds metacognition, as well as adding to the limited literature on methodologies for analyzing data for metacognition. Through its implementation, educators will be able to categorize students' knowledge and thought processes during learning, make extensive use of the concurrent think-aloud protocol by being able to effectively code the data, and present deeper analyses of cognition and metacognition.

CHAPTER 5

CONCLUSION

Over the course of this dissertation, I have presented three separate, but interconnected, studies in order to examine several important areas of scholarship: educational technology, student knowledge of biological and chemical concepts, cognition, and metacognition. My hope is that the information acquired within this research will allow other educators to better utilize modules such as those presented in this study. Additionally, the investigation of cognition and metacognition works both to illuminate and better define the terminology and to observe the way the two work together. In this chapter, I summarize the conclusions and implications from each chapter/study, discuss the overall contributions of the dissertation, and present future directions.

Chapter Conclusions and Implications

Chapter 2. My research detailed in Chapter 2 focused on student participants' use of the modules (which through computer games simulate biological processes at the molecular level) and those modules' usefulness in the science classroom, particularly in regard to how they reflect or enhance students' conceptions of osmosis, diffusion, and filtration. I sought to answer the following research question: In what ways are the students' conceptions of osmosis, diffusion, and filtration represented by their responses to questions both embedded within and external to the modules? I analyzed data from the pre, post and post-post tests of six students, also examining the embedded forced-choice and free-response questions embedded within the modules. While the test score analysis indicated a positive effect on students' knowledge of osmosis, diffusion, and filtration between the pre and post-test, the score difference between students' post and post-post tests showed a marked decline, indicating a regression in students' knowledge. Despite both of these results, I found no statistically significant impact on the test scores as a result of the modules—scores were varied and inconsistent, and as a result did not show a reliable pattern toward increased or decreased knowledge. Students' performance on the modules echoed their test results. There was not a high degree of difference between the modules in terms of score; however, students did seem to score higher on forced-choice questions than on free-response questions, a trend that may have been due to the nature of forced-choice questions (i.e. the chance of guessing the correct answer) versus free-response question (see chapter 2). Overall, the implications from this study suggest that more research is necessary. Assessing the usefulness of the modules proved to be more complicated than previously theorized, a problem that will be remedied in the larger study associated with this dissertation through the use of more student cases. Additionally, both when beginning and at the end of the unit the students' lacked accurate conceptual knowledge of osmosis, diffusion, and filtration, a gap in the study that I attempted to fill with the research shown in Chapter 3.

Chapter 3. Chapter 3 served as both a follow-up and an extension of the study presented in Chapter 2. My initial quantitative examination of the data provided me with very little applicable information, both in terms of assessing the usefulness of the modules and in interpreting students' conceptions of osmosis, diffusion, and filtration. In response to this experience, I attempted a qualitative study, intending to delve more deeply into the nature of the students' knowledge. As such, I chose three concepts common to all of the modules on which to focus and evaluate student knowledge:

A. *Molecule movement*: Molecules travel across a selectively permeable membrane, a process that is central to osmosis, diffusion, and filtration.

B. *Concentration gradients*: Concentration gradients drive the process of molecule movement across membranes and, during this process, molecules move from an area of high concentration to low concentration.

C. *Equilibrium*: Systems tend toward equilibrium and, once it is reached, net flow of molecules ceases (although movement of molecules across membranes continues in equal amounts).

Using the above definitions for the three science concepts within the modules, I sought to answer the following question: How can students' knowledge of molecule movement, concentration gradients, and equilibrium be characterized in different learning contexts, including computer-based modules containing simulations? Using multiple sources of data, including pre, post, and post-post tests, the embedded questions within the modules, transcripts from think-aloud interviews, and drawings that the students made, I created three case studies in order to characterize student knowledge at different stages and through different learning contexts, for example, forced-choice questions and more open-ended on-line interviews without instructor feedback.

Building on the results from my first study, I delved into the difference in results between forced-choice and free-response questions. Correct answers on forced-choice questions showed a measure of rote learning, while correct answers on the free-response questions signified that more meaningful learning had taken place, as the format of the questions required explanatory answers that required a certain level of deeper knowledge. This difference in characterization of knowledge was similarly found in written versus verbal forms of assessment and communication. Although neither form seemed to elicit more accurate knowledge than the other, written and verbal communication often showed different levels of student knowledge. In some instances, for example, students could correctly explain a concept verbally, but not in writing, or vice versa. As discussed in Chapter 3, this difference in knowledge characterization between written and verbal assessments may have been due to the format of the assessment (i.e., being nervous about being interviewed). Alternatively, student participants may have simply lacked the necessary written or verbal communication skills to accurately explain a concept, despite their understanding.

Overall, characterizing students' knowledge over a variety of learning contexts and assessment formats provided extremely interesting results. Despite consistent test scores, the participants maintained misconceptions about all three of the science concepts being tested (molecule movement, concentration gradients, and equilibrium); misunderstandings were represented in both the free-response questions and the think-aloud interviews. These misconceptions affected students' responses within the modules and may have far-reaching implications that extend to other, related science concepts that they will be expected to learn in the future, specifically concepts that build off the knowledge of molecule movement, concentration gradients, and equilibrium, such as higher level chemistry and particle physics. Once again, I found that more research is necessary to fully evaluate the modules' effectiveness within the science classroom, because of the limited number of participants and the problem of pre-existing misconceptions. Despite this limitation, it is clear that characterizing students' knowledge over a variety of learning contexts as a methodological and analytical tool has enormous potential to uncover consistent misconceptions hidden by singular learning contexts.

Chapter 4. My work in chapters 2 and 3 focused on the direct evaluation of student knowledge. In Chapter 4, I turned my focus to students' cognition and metacognition in a more theoretical manner. Reflecting on the process of gleaning information and data from the think-aloud interviews in my earlier research (as outlined in chapter 3), I endeavored to create a model that could be used by future scholars to code think-aloud interview transcripts for cognitive and metacognitive knowledge and monitoring. Consequently, I developed the following research questions to guide my study:

5. To what degree can a synthesis of existing scholarship be used to construct a valid model to direct the coding/analysis of student data resulting from interviews related to metacognition while those students are participating in a science learning task?
6. To what degree can analysis of student metacognition using the model described above result in thorough characterization of student metacognition?

To answer these questions, I began by first delving into the current literature on metacognition, focusing on various scholars and how their theories and definitions of metacognition could inform my model. I then explicated the synthesis of these theories and thus explained my newly created model and applied it to a small subsection of data to illustrate its potential usefulness. Through doing so, I hoped to provide a practical, applicable example of coding student think-aloud interviews to reveal latent thought processes and metacognitive/cognitive attributes that are generally difficult to evaluate.

My research in this vein was more theoretical in nature than that of the previous chapters and, therefore, was lacking in concrete results or conclusions in the traditional sense. I focused instead on the implications of the Cognitive/Metacognitive Coding (CMC) model I had created. The model showed promise as a tool to assess individual learning (i.e. evaluating student performance during an activity). Using the three-tiered version of the CMC model (see Chapter 4), researchers can utilize the coding methodology provided therein to break down data from think-aloud interviews into very specific pieces (single sentences or even phrases), increasing their ability to then categorize these pieces to better understand students' cognitive and metacognitive knowledge and processes. The two-tiered version allows for a more simplistic, yet still fruitful, analytical method that can help educators distinguish between cognition and metacognition, and knowledge and processes, categories that are often conflated. This kind of evaluation will aid instructors in better defining these concepts, and therefore increase their ability to emphasize metacognition in classroom practices, a technique that has been indicated in the literature to aid in deepening student learning. Overall, the CMC model serves to both fill a gap in the literature on metacognition and add to the available tools and methodologies for analyzing data from think-aloud interviews.

Contributions

As the studies detailed within this dissertation fall within different areas of scholarship (technology, cognition, and metacognition), it is difficult to identify singular research contributions as a result of the dissertation as a whole. However, the studies are connected and, taken as a whole, contribute to the field of science education in three ways. The first contribution concerns the modules themselves. Studying students' responses to questions embedded within the modules (chapters 2 and 3) and their thoughts while navigating the modules (chapter 3 and 4) will undoubtedly inform future research on the modules—a relatively new technological tool that is growing in popularity in science classrooms ~~across the United States~~. Additionally, as the grant funding the creation and application of the modules is still active, the modules are continually being revised. As such, the research presented in this dissertation could help inform any future changes made to the modules and could result in a more informed and thus smoother operation of the modules in science classrooms. For instance, the analyses from chapters 2 and 3 showed a clear trend of students scoring higher on forced-choice questions than on free-response questions. We can account for this scoring difference in several different ways. One, we could alter the rubrics designed to assess students' answers to the free-response questions to account for the score difference. Two, we could alter the word format of the free-response questions, making it clear what students need to provide in order to receive full credit (i.e., the inclusion of certain key terms). Three, forced-questions in the modules currently provide immediate feedback to students. Altering this feedback method may diminish the score inflation on forced-choice responses. Using any one of these methods, or a combination of them, may provide researchers and educators with more effective modules. As another example, consider the results from Chapter 3, in which it became clear that students, despite their use of the modules, finished the unit retaining some of the same misconceptions that the modules were designed to specifically address (e.g., recognizing the importance of concentration gradients and their role in osmosis and diffusion). The modules could be edited to more thoroughly address these specific issues, now that we have a better idea of the misconceptions that students continually maintain despite instruction.

A second major contribution of this dissertation concerns students' knowledge. It became clear that, while students may present knowledge of a concept in one context (e.g., written forms of communication), they may retain misconceptions in other contexts (e.g., verbal forms of communication). Thus, characterizing student knowledge over multiple learning contexts provides a fruitful method for scholars seeking to understand not only *what* students know about certain concepts, but also *how* they know those concepts and whether that knowledge is carried over consistently from one context to the next. This contribution has both immediate and future implications. In terms of immediate implications, as discussed above, characterizing students' knowledge over a variety of learning contexts illuminated underlying misconceptions, which (if left unaddressed) have the potential to cloud future researchers' work on the modules and lead to complications concerning these modules' implementation in the classroom. In terms of implications for future research on a larger scale, I believe that characterizing students' knowledge in a variety of learning contexts can be a useful methodology for many scholars, not only for those studying the modules. With the ever-increasing reliance on standardized testing in U.S. schools, instruction in the classroom has become a matter of "teaching to the test." Although more complicated and time-consuming than standardized testing, the evaluation of student learning in multiple contexts (such as the modules, think-aloud interviews, and other open-ended formats) has enormous implications for the classroom, as it can illuminate key misunderstandings preventing students from grasping certain concepts. Not only can this method prove beneficial for individual student learning, but teachers can also use non-test evaluative and learning tools from multiple contexts as a model for classroom instruction, implementing a variety of learning methods in order to determine whether students fully understand the material, or whether they merely understand in one context.

The third contribution of this dissertation centers on the CMC model, drawn from prior literature and my own research, presented in Chapter 4. The CMC model provides researchers with a methodology for coding think-aloud interview transcripts that is grounded in the accepted literature on metacognition. The CMC model can be used in two ways. First: the model provides a way to visualize the aspects of cognition and metacognition that are often conflated. The model also offers a research framework for scholars interested in studying student learning in the classroom, both within and outside of science education. Second: the model can be utilized in a practical manner to evaluate student learning. Although the model was created for the purposes of coding one-on-one think-aloud interview transcripts for cognitive and metacognitive knowledge and monitoring skills, there are many other usages available. For instance, researchers can use the model to observe student learning and categorize the type of learning occurring (metacognitive versus cognitive, declarative versus procedural, etc.).

Overall, the dissertation contributes to several different areas of scholarship in innovative ways. Scholars working on the modules can incorporate changes (see chapters 2 and 3) in order to refine them and resolve some of the issues. Furthermore, the information gained from this study can help scholars evaluate student knowledge by characterizing knowledge over a variety of learning contexts. This method can illustrate not only what concepts students know, but also how they know those concepts. Lastly, the CMC model can be applied in a multitude of ways, both theoretically and practically.

Future Directions

In part because of the need and availability of further case studies, there are many directions that this work can take in the future. As such, I briefly describe in the following pages three studies that could develop the ideas presented in this dissertation. The first is a longitudinal study of students' knowledge of science concepts using the knowledge characterization method as a framework. In this study, I would focus on a large group of high school science students (grades 8-12) over the period of one semester or year. During this time, I would focus on students' knowledge of major science concepts that are discussed in multiple lessons (i.e. the theory of evolution). Focusing on concepts that are taught many times in a variety of contexts over the course of a year would illustrate whether or not students truly understood the major concepts in questions, as well as evaluate their ability to transfer their knowledge from one context to the next, which implies meaningful learning.

The second study would be an expanded analysis of a larger portion of data using the CMC model. The major focus of chapter 4 remained on the creation and presentation of the CMC model, rather than the implementation of it. In the proposed study, I would present a larger analysis of think-aloud interview data, coding entire transcripts from multiple participants, and using the model with each transcript in order to more fully illustrate its usefulness. Additionally, I would break down the analysis using both the three-tiered and two-tiered versions of the model in an effort to discuss and examine the versatility that the CMC model can bring to future analyses.

The third study would also focus on the CMC model, but in this case it would be used as a framework to evaluate classroom instruction, rather than individual student learning. In this research, I would use the CMC model to classify instruction in the science classroom, focusing on three to five teachers over the course of three to six months. Using observations, interviews, and document analysis, I would attempt to characterize their instruction in terms of cognitive and metacognitive knowledge and monitoring. The foundational research of this study thus serves as a base for future expansion of both education research and pedagogical tools.

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APPENDIX A

METACOGNITIVE AWARENESS INVENTORY (MAI)

Mark each of the statements below True or False as appropriate.

1. I consider several alternatives to a problem before I answer.
2. I slow down when I encounter important information.
3. I know what kind of information is most important to learn.
4. I ask myself if I have considered all options when solving a problem.
5. I am good at organizing information.
6. I consciously focus my attention on important information.
7. I have a specific purpose for each strategy I use.
8. I learn best when I know something about the topic.
9. I am good at remembering information.
10. I use different learning strategies depending on the situation.
11. I have control over how well I learn.
12. I periodically review to help me understand important relationships.
13. I think of several ways to solve a problem and choose the best one.
14. I summarize what I've learned after I finish.
15. I am aware of what strategies I use when I study.
16. I focus on the meaning and significance of new information.
17. I create my own examples to make information more meaningful.
18. I find myself using helpful learning strategies automatically.

19. I find myself pausing regularly to check my comprehension.

20. I know when each strategy I use will be most effective.

21. I ask myself if I have considered all options after I solve a problem.

22. I try to translate new information into my own words.

23. I change strategies when I fail to understand.

24. I read instructions carefully before I begin a task.

25. I reevaluate my assumptions when I get confused.

26. I ask myself if I learned as much as I could have once I finish a task.

27. I stop and go back over new information that is not clear.

APPENDIX B

OSMOSIS MODULE RUBRIC

Question	Choices/Answer		
Create a concentration gradient to make oxygen molecules diffuse across the membrane and into the cell	Outside the cell: 0 or 30	Inside the cell: 0 or 30	
What happens to the concentration of free water molecules if you add salt to a solution?	Increase	Decrease	
Predict which way the free water molecules will diffuse?	Out of cell	Into cell	No net diffusion
Predict what would happen to red blood cell if they were placed in: Hypertonic solution	Shrink	Swell	Stay the same
Predict what would happen to red blood cell if they were placed in: Hypotonic solution	Shrink	Swell	Stay the same
Predict what would happen to red blood cell if they were placed in: Isotonic solution	Shrink	Swell	Stay the same
In the image, is the blood hypertonic, isotonic or hypotonic compared to the matrix of the brain?	Hypertonic	Hypotonic	Isotonic
Yes, the blood is hypotonic compared to the matrix of the brain. Now, which way will free water molecules move?	From blood to matrix	From matrix to blood	
What will happen to the pressure in the brain if water moves into it from the blood?	Increase	Decrease	Stay the same
Matrix Sodium - 137	Low	Normal	High
Matrix Pressure - 27	Low	Normal	High
Blood Sodium - 114	Low	Normal	High
Blood Pressure - 22	Low	Normal	High
Neurons Firing Rate - 4.5	Low	Normal	High

Which describes the net free water movement between the blood vessel and matrix?	Into vessel	In equilibrium	Out of vessel
Using the sodium data you collected and what you learned from the Seizure Manual, why are the free water molecules diffusing out of the vessel?	Student mentions water concentration OR mentions sodium concentration	Student mentions sodium or water concentrations but does not clearly connect it or explain it with osmosis.	Student identifies osmosis as the reason water is moving AND Student mentions the greater concentration of sodium in the matrix and explains this as the factor that is causing water to move out of the vessel wall OR Student focuses on the concentration of water inside and outside of the vessel wall as the primary factor in why water is moving out of the cell.
Why is the pressure in the matrix high?	Student states that the matrix pressure will increase	Student states that matrix pressure will increase AND Student explains that more water molecules in the matrix will increase the collisions between molecule and therefore increase the pressure. Student demonstrates a clear understanding of the relationship between area/volume and	Student states that matrix pressure will increase AND Student correctly describes the relationship among all three components (water movement, matrix pressure, firing rate) (Increased water concentration leads to increased matrix pressure which causes abnormal firing rate).

		pressure.	
The following list is not in the correct order. The first 3 events are numbered correctly. Using numbers 4 through 8, label the remaining events in the order that led to Clark's seizures.			
Net movement of free water into the matrix	5		
Loss of sodium ions due to diarrhea (2)			
Normal Blood and Matrix sodium concentrations (1)			
Abnormal Neuron Firing rate	7		
Increased Matrix Pressure	6		
Seizures	8		
Low blood sodium concentration	4		
Excessive intake of water (3)			
Choose a diagnosis from these two options:	Cerebral Edema	Epilepsy	
Explain your decision:	Student writes one correct reason for selecting Cerebral Edema (low concentration of sodium ions in the blood, increased neuron firing rate due to increased matrix pressure, seizures).	Student explains two of the three components that would lead to an explanation of Cerebral Edema.	Student provides a thorough explanation of the relationship between the pressure in the brain matrix and the increased neuron firing rate. Student mentions the low concentration of sodium ions in the blood and student mentions

			symptoms of Cerebral Edema (seizures).
Interpret each as higher, lower, or equal to normal blood Na+ concentration:			
Isotonic saline	Lower	Equal	Higher
Hypotonic saline	Lower	Equal	Higher
Hypertonic saline	Lower	Equal	Higher
Now, rank these 3 saline solutions based on free water concentration:			
Isotonic saline	Lowest	Middle	Highest
Hypotonic saline	Lowest	Middle	Highest
Hypertonic saline	Lowest	Middle	Highest
Based on the data collected and what you have learned about osmosis and the three treatment options, rank the treatments from most effective to least effective.			
Isotonic saline	Least Effective	---------------	Most Effective
Hypotonic saline	Least Effective	---------------	Most Effective
Hypertonic saline	Least Effective	---------------	Most Effective
You have chosen hypertonic saline. Predict the effects of your treatment on the following:			
Blood Sodium Concentration	Decrease	No Change	Increase
Brain Matrix Pressure	Decrease	No Change	Increase
Neuron firing rate	Decrease	No Change	Increase
Net free water movement	Into Vessel	In Equilibrium	Out of Vessel

Justify your answer regarding net free water movement.	During: Student accurately describes what is happening, but does not articulate if there is or is not a difference in the net water movement OR Student indicates the net movement of water is into the vessel but does not explain why		Student explains that there is a difference in the net movement of water into the blood vessel due to the concentration gradient of sodium or water
	After: Student accurately describes what is happening, but does not articulate if there is or is not a difference in the net water movement. Student indicates the net movement of water is into the vessel but does not accurately explain why.		Student explains there is equilibrium in the net movement of water After Treatment AND Student is able to explain why the water is moving into and out of the vessel
The following list is not in the correct order. Starting with Seizures, use numbers 3 through 7 to identify the sequence of events showing how HYPERTONIC SALINE re-established equilibrium and stopped the seizes in Clark's brain.			
Net Movement of Free Water into Vessel	4		
Administer Hypertonic Saline (2)			
Increase in blood sodium concentration	3		
Decrease in neuron firing rate	6		
Decrease In matrix pressure	5		
Seizures (1)			
Seizures stopped	7		

Based on what you have learned, summarize the relationship between solute concentrations on opposite sides of a semi-permeable membrane and the direction of movement of free water molecules.	Student does not accurately explain any part of the relationship between sodium concentration and osmosis.	Student discusses that sodium and water should be balanced, but does not elaborate that this means in terms of concentration.	Student accurately explains the relationship between higher sodium concentrations meaning more water is necessary. Water will move to areas of high sodium concentration.
Patient Summary			
Initial laboratory findings	Free Response		
Treatment Goals	One point for selecting hypertonic for the best treatment option.		May receive up to 3 points total for accurately explaining each of the aforementioned components
How osmosis was involved in causing Clark's seizures	One point for establishing the relationship between osmosis and the seizures.		
How osmosis was used to stop Clark's seizures	One point for establishing the relationship between osmosis and the successful treatment.		
You have chosen hypotonic saline. Predict the effects of your treatment on the following:			
Blood Sodium Concentration	Decrease	No Change	Increase
Brain Matrix Pressure	Decrease	No Change	Increase
Neuron firing rate	Decrease	No Change	Increase
Net free water movement	Into Vessel	In Equilibrium	Out of Vessel
Justify your answer regarding net free water movement.	Student indicates that there is no difference.	Student receives one point for explaining why there is no difference in the net movement of water.	

APPENDIX C

DIFFUSION MODULE RUBRIC

Question	Choices/Answer		
Air is a mixture of gases, including oxygen, nitrogen and carbon dioxide. Choose the correct percentages below:			
Oxygen	0.04%	21%	78%
Carbon Dioxide	0.04%	21%	78%
Nitrogen	0.04%	21%	78%
What effect does the concentration difference have on the rate of diffusion of oxygen?	Decreasing the concentration difference increases the rate of diffusion	Changing the concentration difference has little effect on the rate of diffusion	Increasing the concentration difference increases the rate of diffusion
What effect does the diffusion distance have on the rate of diffusion of oxygen?	Increasing the diffusion distance decreases the rate of diffusion	Changing the diffusion distance has little effect on the rate of diffusion	Increasing the diffusion distance increases the rate of diffusion
When compared to normal, what effect would a shallow concentration gradient have on the rate of diffusion of oxygen?	Slower	No effect	Faster
What effect does the surface area have on the rate of diffusion of oxygen?	Decreasing the surface area increases the rate of diffusion	Changing the surface area has little effect on the rate of diffusion	Decreasing the surface area decreases the rate of diffusion
Compare the admission data to the normal range and select whether the arterial oxygen level is low normal or high: 55	Low	Normal	High

From what you learned in the diffusion manual, what factors could be responsible for the patient's low arterial oxygen?	Students may score a 0-6 based on number of identified factors: (1) Diffusion distance, (2) Concentration difference, (3) Surface Area		*2 points per correct answer /one point if wording is inaccurate
Alveolar Air: 75	Low	Normal	High
Blood entering lungs: 45	Low	Normal	High
Concentration difference: 30	Low	Normal	High
Diffusion distance (microns): 0.46	Low	Normal	High
Surface area (mm2): 0.1	Low	Normal	High
Do the data you have collected support your hypothesis as to why your patient has hypoxemia? Explain why.	Students may score a 0-6 based on answer as well as evidence used to support answer: one point for "yes" or "no" followed by an additional point for each piece of evidence used to support the conclusion		Yes or No, Surface Area, Diffusion Distance, Concentration Difference, One point for correct terminology
You can try these treatments in any order, but see if you can come up with a logical order for their use:			
Diuretic by injections	First	Second	Third
Oxygen by nasal prongs	First	Second	Third
Corticosteroids by nebulizer	First	Second	Third
Explain why you ranked these treatments this way.	Students may score a 1-9	Points for treatment order (1-3), points for time (1-3 points), points for side effects (1-3 points)	
Alveolar Air: 102	Low	Normal	High
Blood entering lungs: 45	Low	Normal	High
Concentration difference: 57	Low	Normal	High
Diffusion distance (microns): 0.46	Low	Normal	High
Surface area (mm2): 0.1	Low	Normal	High

Arterial blood oxygen (mmHG): 69	Low	Normal	High
This treatment has increased your patient's arterial blood oxygen. Why?	One point for increasing concentration difference which in turn increase diffusion rate		
Alveolar Air: 102	Low	Normal	High
Blood entering lungs: 45	Low	Normal	High
Concentration difference: 57	Low	Normal	High
Diffusion distance (microns): 0.46	Low	Normal	High
Surface area (mm2): 0.15	Low	Normal	High
Arterial blood oxygen (mmHG): 83	Low	Normal	High
This treatment has increased your patient's arterial blood oxygen. Why?	One point for increasing surface area of alveoli which in turn increases rate of diffusion		
Alveolar Air: 102	Low	Normal	High
Blood entering lungs: 45	Low	Normal	High
Concentration difference: 57	Low	Normal	High
Diffusion distance (microns): 0.21	Low	Normal	High
Surface area (mm2): 0.15	Low	Normal	High
Arterial blood oxygen (mmHG): 97	Low	Normal	High
This treatment has increased your patient's arterial blood oxygen. Why?	One point for decreasing the diffusion distance which in turn increases rate of diffusion		
Complete the sections below:			
Patient history	Free response		
Patient symptoms	Free response		
Diagnosis	Establish the relationship between treatment and diffusion		

	One point for identifying O2 therapy as treatment option	One point for identifying steroid therapy as treatment option	One point for identifying diuretic as treatment option
How concentration difference, diffusion distance, and surface area were affected by the treatments	One point for establishing relationship between increasing concentration difference of 02 and the increased rate of diffusion	One point for establishing the relationship between decreasing the diffusion distance which in turn increases rate of diffusion	One point for establishing the relationship between increasing the surface area of alveoli which in turn increases rate of diffusion
		One point for establishing relationship between increasing concentration difference of 02 and the increased rate of diffusion	One point for establishing the relationship between decreasing the diffusion distance which in turn increases rate of diffusion

APPENDIX D

FILTRATION MODULE RUBRIC

Question	Choices/Answer				
Upload and interpret data					
Urea: 187 mg/dL	Low	Normal	High		
Potassium: 9.6 mmol/L	Low	Normal	High		
Albumin: 3.2 gm/dL	Low	Normal	High		
Based on Anthony's history, symptoms and the diagnostic test results, select your final diagnosis.	Liver failure	Kidney failure	Heart failure		
Justify your decision below: Students MUST score 1 since the program does not allow the student to move on until kidney failure is chosen.	1 point for mentioning high urea and 1 point for mentioning potassium	1 point for mentioning high urea, 1 point for mentioning potassium, AND 1 point for mentioning normal heart size OR for mentioning normal albumin concentration		1 point for mentioning high urea, high potassium, normal heart size, and normal albumin concentration	
What needs to change so that only the yellow solutes diffuse across the membrane?	Student identifies larger pores or increased pore size				
Solute concentrations: 120:0, 90:30, 60:60. What do you predict concentrations will be at 15 seconds?	60/60	90/30	30/90		

Explain your answer	1 point for noting that the concentration is at equilibrium	1 point for noting that the concentration is at equilibrium AND 1 for relating this to no net particle movement			
Adjust the pore size of the capillary walls to meet the goal below (Filter urea and potassium, keep albumin in blood)	Small	Medium	Large		
Upload and interpret data: Goals met?					
Urea: 45	Yes	No			
Potassium: 6.0	Yes	No			
Albumin: 3.2	Yes	No			
Body mass: 185 lbs	Yes	No			
Upload and interpret data: Goals met?					
Urea: 45	Yes	No			
Potassium: 6.0	Yes	No			
Albumin: 3.2	Yes	No			
Body mass: 185 lbs	Yes	No			
Parallel Flow: Blood: 90, 68, 45, 45, 45. Dialysate: 0, 22, 45, 45, 45.					

In which regions of the filter is there a concentration gradient between the blood and the dialysate?	Region I	Region II	Region III	Region IV	Region V
Now choose which way urea is diffusion by selecting the appropriate arrow icon.					
I	To blood	To dialysate	Even		
II	To blood	To dialysate	Even		
III	To blood	To dialysate	Even		
IV	To blood	To dialysate	Even		
V	To blood	To dialysate	Even		
With parallel flow, diffusion of urea occurred at regions I and II, but not at regions III, IV, or V because…	Urea was too big to go through the pores in regions III, IV, and V	There was no concentration gradient for urea in regions III, IV, or V	There was no urea in the blood in regions III, IV, and V	The pore size was too small in regions III, IV, and V	
Countercurrent Flow: Blood: 90, 74, 58, 42, 26. Dialysate: 64, 48, 32, 16, 0.					
In which regions of the filter is there a concentration gradient between the blood and the dialysate?	Region I	Region II	Region III	Region IV	Region V
Now choose which way urea is diffusing by selecting the appropriate arrow icon.					
I	To blood	To dialysate	Even		
II	To blood	To dialysate	Even		

III	To blood	To dialysate	Even		
IV	To blood	To dialysate	Even		
V	To blood	To dialysate	Even		
With countercurrent flow, diffusion occurred in all regions of the filter. Explain why.	1 point for noting that there is a concentration gradient in all regions of the filter OR 1 point for noting there is no equilibrium		2 points for both, - why would you mention both?		
As you've determined, urea diffused in all regions of the filter during countercurrent flow. Using what you know about the sizes of urea and potassium, what would potassium do during countercurrent flow?	Diffuse in all regions of the filter	Diffuse until equilibrium is reached in regions III, IV, and V			
Explain your answer.	1 point for noting the relative size of potassium to urea OR for noting that potassium would diffuse in all regions of the filter	1 points for noting the relative size of potassium to urea AND 1 point for noting that there is a concentration gradient in all regions of the filter during countercurrent flow OR that potassium will diffuse in all regions		3 points for noting the relative size of potassium to urea, that there is a concentration gradient in all regions of the filter during counter-current flow, and that potassium will diffuse in all regions of the filter	
At the end of countercurrent flow, Anthony's mass had decreased to reach his goal. What happened during dialysis to cause the decrease in Anthony's mass?	1 point for noting water is removed during dialysis				

During parallel flow there was a concentration gradient for albumin in all regions of the filter. The same was true for countercurrent flow. However, albumin never diffused into the dialysate. Why not?	Albumin molecules are too large to fit through the pores in the membrane	Student discusses the semi-permeable nature of the walls of the filter tubes and relates this to how albumin molecules are too large to fit though the pores.	
Patient summary	Free response		
Treatment goals	Free response		
How diffusion was involved in reaching goals	1 point for mentioning potassium diffusion and 1 point for relating this to the concentration gradient in the counter-current flow AND 1 point for mentioning urea diffusion and 1 point for relating this to the concentration gradient in the counter-current flow		
How filtration was involved in reaching goals	1 point for mentioning lack of albumin filtration and 1 point for connecting this to particle size and the semi-permeable nature of the membrane		
How body mass is returned to normal	1 point for noting water removal		
Why countercurrent flow was better than parallel flow	2 points for noting there is a concentration gradient so diffusion occurs in every region for counter-current flow AND 1 point for noting equilibrium in parallel flow		

APPENDIX E

POST-INTERVIEW QUESTIONS

Osmosis

1. What was your favorite part of the Osmosis case study?
2. When you think about the Osmosis case study, what is the first thing you remember?
3. What scientific concepts do you remember from this case?
4. Were you successful in making Clark better?
    a. Were you successful on the first try?
    b. What treatment worked?
    c. How did the treatment work?
5. Why did water move in a particular direction?
6. What effect does this water movement have on the pressure? Why?

Dialysis

1. What was your favorite part of the Dialysis case study?
2. When you think about the Dialysis case study, what is the first thing you remember?
3. What scientific concepts do you remember from this case?
4. What was wrong with Anthony? Look at this screen shot from the program, is this showing the system working correctly?
5. How difficult was it for you to identify the correct filter size?
6. You saw the blood going into the dialysis filter:

a. Where did the blood go?

b. How did the dialysis filter clean the blood (remove potassium and urea from Anthony's blood)?

Diffusion

1. What is your favorite part of the Diffusion case study?
2. When you think about the Diffusion case study, what is the first thing you remember?
3. What scientific concepts do you remember from this case?
4. What did the chlorine gas do to the patient?
5. Were you able to help the person who inhaled chlorine gas?
6. How did you treat the patient?
7. After the person inhales chlorine, she was having difficulty breathing. What happened that was making it difficult for her to breathe?

APPENDIX F

COGNITIVE/METACOGNITIVE CODING MODEL KEY

Level 1	Level 2	Level 3	Level 3 Descriptions	Code	Example
Cognition: The first level of understanding, knowing what and knowing how you know	*Declarative:* What You Know	Factual	Terminology, specific details	CK1	Plants use photosynthesis to make energy
		Conceptual	Principles, generalizations, theories	CK2	The process of photosynthesis is this
		Procedural	Subject-specific skills, techniques, methods	CK3	I can use the process of paper chromatography to separate the primary pigments in leaves
	Procedural: How You Know	Remember	Recognizing, recalling	CM1	Plants use photosynthesis to make energy because I read it in a book
		Understand	Interpreting, determining meaning	CM2	Plants use photosynthesis to make energy because plants use carbon dioxide and create oxygen, which is how photosynthesis works
		Apply	Executing, implementing a procedure	CM3	Plants are green because I used the process of paper chromatography to separate the primary pigments in leaves
		Analyze	Organizing, relating parts to overall structure	CM4	Plants are an important part of the larger ecosystem because they produce oxygen and use carbon dioxide, which is the process opposite of animals
		Evaluate	Judging based on criteria, checking,	CM5	This is a plant and this is not a plant because it does not absorb light or

			critiquing		photosynthesize
		Create	Generating, planning, producing, making an original product	CM6	Plants look green (i.e. reflect green light) because I made a model of this using a flashlight and some green cellophane
Metacognition: Awareness of knowledge, ability to transfer knowledge to other concepts, and control of cognitive processes	*Knowledge:* What You Know	Factual	Terminology, specific details	MK1	Student exhibits awareness of knowledge, ability to transfer knowledge, or control over cognitive processes: Can come in the form of self-assessments, relating material to other subject areas, or knowing which skill to use when learning
		Conceptual	Principles, generalizations, theories	MK2	
		Procedural	Subject-specific skills, techniques, methods	MK3	
	Monitoring: How You Know	Remember	Recognizing, recalling	MM1	
		Understand	Interpreting, determining meaning	MM2	
		Apply	Executing, implementing a procedure	MM3	
		Analyze	Organizing, relating parts to overall structure	MM4	
		Evaluate	Checking, critiquing	MM5	
		Create	Generating, planning, producing, making an original product	MM6	