ABSTRACT

COOK, MICHELLE PATRICK. Surface and Semantic Processing of Cellular Transport Representations by High School Students with Low and High Prior Knowledge. (Under the direction of Glenda Carter and Eric Wiebe.)

The purpose of this study was to examine the influence of prior knowledge of cell transport processes on how students viewed and interpreted visual representations related to that topic. The participants were high school students \((n=65)\) enrolled in Advanced Placement biology. Prior knowledge was assessed using a modified version of the Diffusion and Osmosis Diagnostic Test (Odom & Barrow, 1995). Eye movements were measured to reveal how students distribute their visual attention as they perceive and interpret graphics; in addition, interviews and questionnaires were employed to provide more interpretive data sources.

The first manuscript of the study investigates the relationship between prior knowledge and students’ ability to perceive salient features and interpret graphic representations of cellular transport. The results from eye tracking data, interviews, and questionnaire responses were triangulated and revealed differences in how high and low prior knowledge students attended to and interpreted various features of the graphic representations. Without adequate domain knowledge, low prior knowledge students focused on surface features of the graphics to build an understanding of the concepts represented. High prior knowledge students, with more abundant and better organized domain knowledge, were more likely to attend to thematically relevant content in the graphics and construct deeper understandings.
The second manuscript of the study examines the influence of prior knowledge on how students transitioned among the macroscopic and molecular representations of selected graphics. Eye tracking and sequential analysis results indicated that high prior knowledge students transitioned more frequently between the molecular representations, whereas low prior knowledge students transitioned more frequently between the macroscopic representations. In addition, low prior knowledge students transitioned more frequently between macroscopic and molecular representations, suggesting that these students were experiencing more difficulty as they were coordinating the representations. These findings suggest that students with high prior knowledge distributed their visual attention on conceptually relevant features, while low prior knowledge students focused on surface features.
SURFACE AND SEMANTIC PROCESSING OF CELLULAR TRANSPORT REPRESENTATIONS BY HIGH SCHOOL STUDENTS WITH LOW AND HIGH PRIOR KNOWLEDGE

By
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

SCIENCE EDUCATION

Raleigh, NC 2006

APPROVED BY:

_________________________          _________________________
Co-chair of Advisory Committee          Co-chair of Advisory Committee
DEDICATION

To my husband, Charles, whose support and sacrifice have made this endeavor possible; to my parents, who have always encouraged me to accomplish my goals.
BIOGRAPHY

Michelle Patrick Cook was born to Ronnie and Kazuko Patrick in 1975. She was raised, along with her older brother Sean, in California, Japan, South Carolina, and North Carolina. She spent much of her childhood on military bases attending Department of Defense schools. Michelle’s experiences in high school were especially influential in guiding her career decisions; she had several exemplary teachers, one of whom sparked her interest in biology. After high school, Michelle continued her studies at the University of North Carolina at Chapel Hill, receiving a Bachelor of Science in Biology and a Master of Arts in Teaching in Science Education.

Upon graduation, Michelle accepted a position at Cardinal Gibbons High School in Raleigh, NC, where she taught College Preparatory Biology, Honors Biology, and Advanced Placement Biology. After teaching for a few years, she made the decision to begin work on her Ph.D. in Science Education by taking courses on a part-time basis. When her coursework was completed, Michelle left the classroom to continue her studies as a full-time student. Since that time, she has worked as a research assistant for a grant sponsored by the GlaxoSmithKline Foundation. After graduation, Michelle will begin at Clemson University, as an Assistant Professor of Science Education.
ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my committee co-chairs—Dr. Glenda Carter and Dr. Eric Wiebe. I appreciate Dr. Carter’s ability to provide the right amount of support at my precise time of need; she has generously shared her time and has been an excellent mentor. Special thanks to Dr. Wiebe for his ability to challenge me intellectually as I became familiar with a new body of literature; our conversations have been thought-provoking and he has helped refine my research skills.

I also would like to extend my sincere gratitude to my committee members—Dr. John Meyer, Dr. John Park, and Dr. John Penick. I am very appreciative of your helpful comments throughout this research project, as well as your guidance and advice throughout my studies in general.

I would like to acknowledge others who have made this research possible. I am grateful to Bethany Smith for her assistance with data collection. Special thanks to the administration, faculty, and staff of Cardinal Gibbons High School for allowing me to return to conduct my research and accommodating my needs. In particular, I would like to thank Susan Goethals for letting me work with her students.

Finally, I would like to express my gratitude to my family. Thanks to my parents for their steadfast confidence in my abilities; when I needed a lift in spirit, I knew who to call. And to my husband Charles, thank you for your unwavering support, even during the times when it appeared that my dissertation was my first priority.
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INTRODUCTION

Research on instructional representations has been an area of particular interest in science education. The science classroom is saturated with representations of scientific concepts and it is through these representations that knowledge is communicated from teacher to students (van Someren et al., 1998). Although the importance of visual representations in science education has been established, more research is necessary on how to best facilitate learning with graphics. Teachers and instructional designers believe that graphics have a great deal of potential as meaning-making resources, yet in practice, visual representations do not always live up to this potential (Roth, Bowen, & McGinn, 1999). To understand the role of visual representations in science education, we must consider not only the way they are designed, but also the way they are received by different learners (Pozzer-Ardenghi & Roth, 2005). Examining how differences in learner characteristics, such as prior knowledge, influence how learners perceive and interpret visual representations is an important first step in designing more effective instructional materials.

Although expert and novice differences are clear in the literature, the influence of prior knowledge on students’ interpretation of visual representations is still in its infancy. While most of the research addresses differences between experts and novices, in reality, the situation is not that simple. Students cannot merely be categorized as experts or novices; instead, they represent a continuum of prior knowledge. Because it is unclear whether more or less proficient novices differ in the same manner as experts and novices, the goal of this research was to more fully explore the expert-novice continuum and discover how
differentially prepared students viewed and interpreted graphics. The findings have implications for the design of visual representations.

The purpose of this study was to examine how prior knowledge related to cellular transport influenced how Advanced Placement Biology students viewed and interpreted visual representations related to that topic. Specifically, the following research questions were addressed in this dissertation:

1. What features do students with different levels of prior knowledge use to interpret graphics?
2. How does the amount of prior knowledge influence the level of processing difficulty experienced by students?
3. How do students with differing levels of prior knowledge transition between features of the graphic?
4. How does prior knowledge influence how students interpret visual representations of passive and active transport on a macroscopic level? On a molecular level?

This research utilized both quantitative and qualitative research methods, allowing for comprehensive analysis and triangulation of multiple data sources. After assessing the prior knowledge of participants, the study was divided into two phases. In Phase 1, data was collected using eye tracking and interviews. Over the course of one month, participants were eye tracked as they viewed a series of seven representations and then interviewed about those representations. After this first phase was completed, classroom instruction on cellular membrane structure and function began. Students received normal classroom instruction on cell membrane structures and processes, but were asked to fill out questionnaires on eight of the representations the teacher used in her instructional presentations. A subset of students
was interviewed to elaborate on the questionnaire data. At the culmination of this unit, students took a teacher-designed posttest that included additional items asking students to interpret and create visual representations.

Two articles have emerged from the data collected. The first manuscript, *The Interpretation of Cellular Transport Graphics by Students with Low and High Prior Knowledge*, addresses research questions 1 and 2. The second manuscript, *The Influence of Prior Knowledge on Viewing and Interpreting Graphics with Macroscopic and Molecular Representations*, addresses research questions 3 and 4.

Following the two articles is an executive summary that reviews the findings of the articles as well as implications. The prospectus, *The Influence of Prior Knowledge on High School Students’ Interpretations of Visual Representations of Cellular Transport Processes*, has been included in the appendix.
The Interpretation of Cellular Transport Graphics by Students with Low and High Prior Knowledge
Abstract

The purpose of this study was to examine how prior knowledge of cellular transport influenced how high school students viewed and interpreted graphic representations of this topic. The participants were Advanced Placement Biology students ($n=65$); each participant had previously taken a biology course in high school. After assessing prior knowledge using the Diffusion and Osmosis Diagnostic Test (Odom & Barrow, 1995), two graphical representations of cellular transport processes were selected for analysis. Three different methods of data collection—eye tracking, interviews, and questionnaires—were used to investigate differences in perceived salient features of the graphics, interpretations of the graphics, and processing difficulty experienced while attending to and interpreting the graphics. The results from the eye tracking data, interviews, and questionnaire responses were triangulated and revealed differences in how high and low prior knowledge students attended to and interpreted particle differences, concentration gradient, the role of ATP, endocytosis and exocytosis, and text labels and captions. Without adequate domain knowledge, low prior knowledge students focused on the surface features of the graphics (ex. differences in particle color) to build an understanding of the concepts represented. On the other hand, with more abundant and better organized domain knowledge, high prior knowledge students were more likely to attend to the thematically relevant content in the graphics and construct deeper understandings. The findings of this study offer a more complete understanding of how differentially prepared learners view and interpret graphics and have the potential to inform instructional design.
The Interpretation of Cellular Transport Graphics by Students with Low and High Prior Knowledge

Introduction

Visual Representations

Research on instructional representations has been an area of particular interest in science education. The science classroom is inundated with representations of scientific phenomena used to convey content knowledge to students (van Someren et al., 1998). In particular, graphics are ideal for representing abstract and invisible concepts in science that are difficult to describe with text alone (Buckley, 2000). They are also useful when communicating multiple relationships and processes. Visual representations can attract attention and motivate students (Mayer et al., 1996), as well as improve retention (Peeck, 1993) and facilitate linkages between new knowledge and existing knowledge (Roth, Bowen, & McGinn, 1999). In general, visual representations provide another way to represent information and have the potential to increase conceptual learning (Cheng, 1999).

Well-designed visual representations have the potential to promote active cognitive processing by learners. Students are not cognitively passive as they approach learning from visual representations; they actively construct knowledge on the foundation of their existing knowledge (Taber, 2001). To understand a topic fully, learners must make sense out of ideas that make up a concept as well as have relevant conceptual knowledge to anchor new ideas. It is a learner’s framework of relevant concepts that allows him or her to make sense out of new ideas; when these prior concepts are lacking or inappropriate, the learner has difficulty acquiring new information in the intended manner (Johnson & Lawson, 1998).
Mayer and his colleagues have proposed the cognitive theory of multimedia learning which suggests that learners engage in several active cognitive processes as they construct a mental representation of the instructional material (Mayer & Anderson, 1991; Mayer & Moreno, 2003). When both visual and verbal information are presented to the learner in instructional materials, they are briefly represented in sensory memory. Because the human information processing system is not unlimited in capacity, only some of the visual and verbal representations will be selected for processing in working memory. Relevant images and words from the graphic will be selected for further processing in visual and verbal working memories, respectively.

Next, the selected images and words will be organized into coherent models (Kintsch, 1988). Internal connections will be made among the selected images to yield a visual mental model. Likewise, a similar process will occur with the selected words to create a verbal mental model (Mayer, 1999). The final step involves building external connections between the resulting visual and verbal mental models. This building of referential connections between corresponding visual and verbal elements also requires the integration of relevant prior knowledge. It is this integrated representation that will be stored in long-term memory.

**Prior Knowledge**

Prior knowledge is one of the most influential factors affecting learning from visual representations. Mayer’s (1999) cognitive theory of multimedia learning asserts that relevant prior knowledge facilitates the one-to-one connections made between the visual and verbal mental models. However, prior knowledge also influences the earlier stages in this model. Prior knowledge affects which images and words are selected for processing in working memory and how they will be organized into coherent visual and verbal mental models
(Braune & Foshay, 1983). The assertion that prior knowledge influences the cognitive process involved in constructing understanding from instructional representations is supported by research findings related to differences between expert and novice learners. Most of the research involves differences in problem-solving strategies between experts and novices; however, the findings of these studies may offer an explanation for differences found in knowledge acquisition from visual representations as well.

Novice learners are assumed to have less prior knowledge of the domain to use as a foundation for building mental representations from instructional materials. What knowledge they do have is not heavily interrelated and not hierarchically organized into a framework to make sense of new information (Johnson & Lawson, 1998). Because their prior knowledge is lacking and weakly organized, novice learners are left with few reference points for new learning. Therefore, they focus on superficial aspects of representations (Heyworth, 1999) and the mental models they develop tend to be superficial (Snyder, 2000).

Experts have more domain knowledge, but even more important, the knowledge they have is well organized. This complex, elaborate network of prior knowledge allows expert learners to better link their mental representations to related principles of content (Geelan, 1997). These learners are able to choose appropriate schema to help understand new information. Because their understanding is not merely descriptive, experts develop more abstract mental models in comparison to novices (Snyder, 2000).

Although the research on expert-novice differences is abundant in the literature, very few studies have investigated the influence of prior knowledge with respect to visual representations. More studies examining how prior knowledge influences how students view and interpret these representations are necessary to determine if previous findings related to
expert-novice differences are applicable in this context. In addition, while expert-novice differences are informative, most students in the classroom do not neatly fall into these categories. If one envisions prior knowledge as a continuum, students typically fall somewhere in between the two extremes of expert and novice. Therefore, more research is also necessary to determine if students with more or less prior knowledge in the middle of this continuum differ in the same manner as experts and novices. The goal of this study is to advance knowledge of how differentially prepared learners, specifically students considered to be more and less proficient novices, understand visual representations.

Methodology

Rationale for Topic Selection

During the past few decades, research in science education has indicated that students of all ages have difficulty understanding basic biological processes (Arnaudin & Mintzes, 1985; Johnstone & Mahmoud, 1980; Lawson & Thompson, 1988). Specifically, middle school, high school, and college students have many misconceptions about diffusion and osmosis (Odom & Barrow, 1995; Westbrook & Marek, 1991). For example, Marek (1986) administered concept evaluation statements to tenth grade biology students to measure their understanding of diffusion and found that 37.5 percent demonstrated a sound to partial understanding of diffusion. In other words, fewer than half of the students participating in the study exhibited any degree of understanding of diffusion; the rest of the students revealed specific misconceptions or offered no response at all. Diffusion and osmosis are fundamental concepts in biology curricula and are keys to understanding the exchange of substances between cells and their environment, and water transport and balance in living organisms.
Therefore, it is important to target these misconceptions, which are often resistant to change despite repeated classroom instruction.

Recently, intervention has focused on using more effective teaching strategies, such as the learning cycle to improve understanding of these topics (Marek, Cowan, & Cavallo, 1994; Odom & Kelly, 2001); nevertheless, misconceptions seem to persist even after repeated exposure to these concepts. Since meaningful understanding of cellular transport requires visualization at macroscopic, microscopic, and molecular levels (Friedler, Amir, & Tamir, 1987; Sanger, Brecheisen, & Hynek, 2001), a more appropriate area of research may involve developing effective visual representations. These representations could serve to help students grasp the abstract concepts necessary for complete understanding of the topic. However, developing effective instructional representations requires an understanding of how current graphics are interpreted by differentially prepared learners, particularly those with varying amounts of prior knowledge.

**Research Questions**

This study represents one part of a larger project designed to examine how high school students’ prior knowledge of a domain influenced how they viewed and interpreted visual representations of cellular transport processes. Two graphics, similar in terms of the content represented, were selected for analysis. The representations selected were typical of what one would find in biology textbooks and supplementary materials, although they were modified to include a minimal amount of text in the form of captions and labels. These graphics were investigated using different methodologies to examine how prior knowledge of cellular transport influenced: (1) what features were salient in the graphic, (2) how those
features were explained, and (3) what level of processing difficulty was experienced by students as they viewed and interpreted those features.

After assessing the prior knowledge of participants, this study was divided into two phases. In phase 1, participants were eye tracked as they viewed a cellular transport graphic to determine the salient features as well as the level of processing difficulty students experienced as they attended to those features. Immediately following the eye tracking session, students were interviewed about the graphic to assess their interpretations. In phase 2, perceived salient features, processing difficulty, and interpretations of the second representation were assessed using a questionnaire.

Participants

Sixty-five high school seniors participated in the study (44 females, 21 males). The students were enrolled in one of three Advanced Placement (AP) Biology courses taught by the same teacher. Most of these students had previously taken biology as freshman and chemistry as sophomores. Students were required to have a grade of an A or A+ in Biology (or a B or B+ in Honors Biology) and an A or A+ in Chemistry (or a B or B+ in Honors Chemistry). Many of the students enrolled in this course had most recently taken either Physics or AP Chemistry.

Prior Knowledge Assessment

Prior knowledge was assessed using a modified version of Odom and Barrow’s (1995) Diffusion and Osmosis Diagnostic Test, or DODT. This 24-item, two-tier multiple-choice instrument was originally developed from research concerning alternate conceptions and other errors commonly made by students. The first tier consists of a content question with two to four choices; the second tier presents four possible reasons for the answer given
in the first part. Three of the choices are common misconceptions related to the content area and once choice reflects understanding of the concept. Topics assessed by the DODT include the particulate and random nature of matter, concentration and tonicity, kinetic energy of matter, membranes, and the processes of osmosis and diffusion.

Since the DODT does not cover all membrane transport processes, items were included to cover membrane permeability, active transport, and endo/exocytosis. These additional items were created by asking a group of high school biology students to answer free response questions in order to detect the common misconceptions that would be used as distracters in the second-tier questions. Following the creation of six new items, the modified, 30-item DODT was piloted with a different group of high school biology students. Other minor changes were made to the modified DODT as a result of a group discussion eliciting students’ comments about the test.

The DODT was scored to determine whether students had low or high prior knowledge about cellular membrane structures and functions. For each of the 15 pairs of questions, a student could score a maximum of three points, or a total raw score of 45 points. A correct answer on the first-tier question received one point, while a correct answer of the second-tier justification question received two points. The first- and second-tier questions received different point values since correctly answering the content question may reflect memorization of the concept; however, a correct response on the justification question indicated deeper understanding. It is important to note that students were not given points for correct second-tier responses unless they correctly answered the first-tier question. Therefore, students did not receive points for merely guessing correctly on second-tier questions without understanding the concept.
All 65 participants completed the DODT. With a total of 45 points possible, scores ranged from 11 to 39 (M=24.2). Based on their DODT scores, participants were divided into three groups to differentiate those with low prior knowledge from those with high prior knowledge. Because of the small sample sizes, students with low prior knowledge (bottom-third) were compared to students with high prior knowledge (top-third) with effect size using Cohen’s $d$ (Cohen, 1988) to assure meaningful differences between the groups. The students with the lowest scores on the DODT ($n=21$, $M=17.2$, range 11-20) showed meaningful differences from the students with the highest scores on the DODT ($n=23$, $M=31.7$, range 28-39) ($d=-1.24$). The students in the middle-third, with a middle range of prior knowledge were not analyzed in this study.

Of the 65 students completing the DODT, 54 students successfully participated in phase 1. From the pre-assessment results, 16 of the 54 students were determined to have a low level of prior knowledge, while 20 of the 54 students had a high level of prior knowledge. Sixty students participated in phase 2. From the pre-assessment results, 18 of the 60 students were determined to have a low level of prior knowledge, while 21 of the 60 students were determined to have a high level of prior knowledge.

**Phase 1—Data Collection and Analysis**

After prior knowledge was assessed, the first phase of the study involved collecting data on eye movement measures to provide a view of how students with differing levels of domain knowledge acquired information from the graphic selected for study. Eye tracking provides a direct measure of how visual attention is allocated, and in this study was used to reveal (1) what features students attended to while viewing the graphic, and (2) what level of processing difficulty students experienced as they made sense of the graphic. A video-based
combined pupil and corneal reflection eye tracker (Applied Sciences Laboratories—ASL Model 504) was used to collect eye movement measures. First, a headset was mounted on the participant’s head. Next, a mirror on the headset was adjusted so that infrared light was reflected into the eye, creating pupil and corneal reflections. Once the subject was calibrated to the computer screen, the relative movement of these reflections was used to calculate where the subject’s eye was focused. The presentation the students viewed was system-paced, and the graphic selected for analysis in this study was eye-tracked for 35 seconds.

The eye tracking graphic, Overview 1 (Figure 1), selected for analysis provided a summary of five different cellular transport processes. First, look zones were defined around areas of interest in the graphic. The eye tracker was used to measure the number of fixations and the average fixation duration (in seconds) for each subject in each look zone. Fixations occur when the eye is stabilized over an area of interest and are commonly defined as lasting at least 200 milliseconds (Duchowski, 2002). Fixations are separated by saccades, or the “jumps” between fixations. Since individuals fixate on areas that are considered to be interesting or important (Goldberg & Kotval, 1999; Henderson, 1992), fixation count (or the number of fixations) is a measure of saliency. The length of a subject’s fixations within a zone, or average fixation duration, is a measure of processing difficulty (Antes, Chang, & Lenzen, 1985; Goldberg & Kotval, 1999). Mean fixation counts and average fixation duration of low and high prior knowledge students were compared with effect sizes, using Cohen’s $d$. Cohen’s $d$ was used due to the small sample sizes of the two groups of students; effect sizes greater than +/-0.80 were considered to be large (Cohen, 1988; Kramer & Rosenthal, 1999).
Following eye tracking, interviews were conducted to provide a more interpretive data source. The combined use of eye tracking and interviewing has shown to be effective in numerous studies (Mackworth & Morandi, 1967; Patrick, Carter, & Wiebe, 2005; von Kietz, 1988). Whereas, eye tracking can provide a direct view of how learners are acquiring perceptual information, interviews can provide information on how learners are interpreting the underlying content. In this study, students were shown the same graphic they viewed as they were eye tracked, and asked the following questions:

- Describe the most obvious features of this graphic.
- Explain what you think this graphic is trying to communicate.
- What suggestions do you have to improve this graphic?
The interview responses were used to complement the eye tracking data. For example, the students’ descriptions of salient features were compared to fixation count measures. Likewise, students’ difficulties in interpretation were compared to average fixation duration measures. Overall, the interview data provided a more detailed look into how students with lower and higher levels of prior knowledge acquired content information from the graphic.

**Phase 2—Data Collection and Analysis**

In the second phase of this study, students' interpretations of a visual representation selected by the teacher for classroom instruction were examined. During the teacher's presentation on membrane structure and function, the students were shown this graphic and their interpretations of the graphic prior to teacher explanation were assessed by an instructional representation questionnaire which included the following questions: (1) Describe the most obvious features of the graphic (i.e. What stands out to you?), (2) Explain (in as much detail as you can) what you think this graphic is trying to communicate, and (3) What suggestions do you have to improve this graphic?

The graphic, Overview 2 (Figure 2), selected for analysis in this phase was very similar to the eye-tracked graphic in that it presents another summary of cellular transport processes. The responses from the questionnaires were analyzed using the constant comparative method (Strauss & Corbin, 1998). Initially, the data from each question were coded to develop categories; however, a key strategy was to constantly compare these categories. Categories that emerged were compared from one participant to the next, to allow for categories to be interrelated and refined, so that the patterns in how low and high prior knowledge students interpret graphics could be discovered (Hatch, 2002).
Results

Because the two graphics were similar in terms of the content represented, themes emerging from this study were supported by triangulating eye tracking, interview, and questionnaire responses. From the two graphics selected, differences between high and low prior knowledge students emerged in how they attended to and interpreted particle differences, concentration gradient, ATP, endocytosis and exocytosis, and text in the form of labels and captions.

Particle Differences

In Overview 1, there were meaningful differences between the mean fixation counts of low and high prior knowledge students in look zone C (see Table 1). Students with low levels of prior knowledge fixated more in look zone C (M=13.57) than students with high
levels of prior knowledge (M= 9.94) (d=0.81). From the interviews, it seems that many low prior knowledge students were actually focused on the particles represented in the passive transport graphic. Noticing a color and shape difference in the particles as compared to the diffusion graphic, the following quote illustrates that students were trying to discover a reason for these differences.

*Low PK Student:* The particles in this picture are different

*Interviewer:* How are those particles different?

*Low PK Student:* From biology I know it has to do with size or something like that, but it doesn’t really specify that here.

This student appears to recall something from her previous biology course, but not the extent of the following student with high prior knowledge.

*High PK Student:* Those [substances] are going through the lipid bilayer [in the diffusion graphic] and those [substances] have to go though the little guy (referring to protein).

*Interviewer:* Why do you think they have to go through that “guy” versus the lipid bilayer?

*High PK Student:* Because of polarity and their size.

*Interviewer:* So what is the picture trying to communicate about these molecules [in the diffusion graphic] in terms of their polarity and size?

*High PK Student:* They’re obviously different, that’s a circle and that’s a square. They’re smaller and nonpolar.

*Interviewer:* Nonpolar?

*High PK Student:* Yeah, because they have to get through the nonpolar lipids.

High prior knowledge students were able to extract meaning from the color and shape differences of the particles and deepen their understanding of the various transport processes. Low prior knowledge students found this zone to be salient (as indicated by fixation count results), however were unable to interpret meaning from the particle differences. From the interviews, the differences in particle color and shape may not have been the only reason for high fixation counts from low prior knowledge students. It is also possible that some students with low prior knowledge found this zone to be salient because they had difficulty
understanding why two proteins were represented for passive transport. A few students were able to interpret that the graphic was trying to show different methods of passive transport, but many were unable to decipher what the projection on the second protein was trying to illustrate.

*Interviewer:* And then you said there are two things (proteins) here? Is there a reason why this second one is here? Are they trying to show you something different?

*Low PK Student:* Yeah, I don’t know why but I can obviously tell they are trying to show something. There is reason that this has two, but I don’t know.

Table 1.

*Fixation counts of low and high prior knowledge students by look zone*

<table>
<thead>
<tr>
<th>Look Zone</th>
<th>Low Prior Knowledge</th>
<th>High Prior Knowledge</th>
<th>Cohen’s d</th>
<th>* indicates large effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-concentration gradient</td>
<td>4.07 (2.40)</td>
<td>6.34 (2.95)</td>
<td>-0.85*</td>
<td></td>
</tr>
<tr>
<td>B-diffusion graphic</td>
<td>5.57 (3.01)</td>
<td>5.30 (3.02)</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>C-passive transport graphic</td>
<td>13.57 (4.03)</td>
<td>9.94 (4.93)</td>
<td>0.81*</td>
<td></td>
</tr>
<tr>
<td>D-active transport graphic</td>
<td>7.14 (4.00)</td>
<td>9.50 (3.52)</td>
<td>-0.63</td>
<td></td>
</tr>
<tr>
<td>E-energy input</td>
<td>3.64 (2.13)</td>
<td>2.25 (1.18)</td>
<td>0.84*</td>
<td></td>
</tr>
<tr>
<td>F-lipid bilayer</td>
<td>1.50 (1.22)</td>
<td>1.27 (1.37)</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>G-diffusion text</td>
<td>2.79 (3.12)</td>
<td>4.08 (3.29)</td>
<td>-0.40</td>
<td></td>
</tr>
<tr>
<td>H-passive transport text</td>
<td>2.43 (1.55)</td>
<td>3.01 (2.47)</td>
<td>-0.29</td>
<td></td>
</tr>
<tr>
<td>I-active transport text</td>
<td>1.57 (1.22)</td>
<td>1.32 (0.99)</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>J-exocytosis graphic</td>
<td>9.64 (3.52)</td>
<td>9.19 (5.43)</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>K-endocytosis graphic</td>
<td>5.93 (2.79)</td>
<td>8.91 (4.25)</td>
<td>-0.85*</td>
<td></td>
</tr>
<tr>
<td>L-exocytosis text</td>
<td>1.07 (1.14)</td>
<td>0.30 (0.55)</td>
<td>0.91*</td>
<td></td>
</tr>
<tr>
<td>M-endocytosis text</td>
<td>1.07 (1.07)</td>
<td>1.05 (1.24)</td>
<td>0.22</td>
<td></td>
</tr>
</tbody>
</table>

Color was a very salient characteristic for both low and high prior knowledge students in Overview 2 as well. Students indicated that the most obvious features in this graphic were the green proteins, the yellow ATP, and the colored particles. Fifty-seven percent of high prior knowledge students and 56 percent of low prior knowledge students indicated that the different colored particles were eye-catching (see Table 2). However,
when distinguishing the different types of transport processes illustrated in Overview 2, low prior knowledge students (50%) were more likely to talk about the characteristics of the particles passing through the membrane in terms of color than high prior knowledge students (14%).

*Low PK Student:* [In the first picture] the blue circles move through the semi-permeable membrane without any outside assistance. In facilitated diffusion, the red circles are aided by a transporter, but the transporter does not change for the particles at all.

On the other hand, students with high prior knowledge (48%) were more apt to discuss the particle differences in terms of size and polarity than students with low prior knowledge (11%).

*High PK Student:* There are two ways for passive transport: one through the bilayer meaning the molecule doesn’t get repelled because it has the same polarity, and the other through a protein because it doesn’t have the same polarity as the bilayer. So the blue molecules must not be polar and the red are.

<table>
<thead>
<tr>
<th>Questionnaire Response</th>
<th>Low Prior Knowledge</th>
<th>High Prior Knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorful features are salient (ex. green protein)</td>
<td>56</td>
<td>57</td>
</tr>
<tr>
<td>Particle differences explained in terms of color</td>
<td>50</td>
<td>14</td>
</tr>
<tr>
<td>Particle differences explained in terms of size, shape, polarity</td>
<td>11</td>
<td>48</td>
</tr>
<tr>
<td>Used concentration differences to explain different processes</td>
<td>11</td>
<td>67</td>
</tr>
<tr>
<td>Understanding of ATP</td>
<td>17</td>
<td>62</td>
</tr>
<tr>
<td>Suggested more labels/text explanation</td>
<td>72</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 2. A comparison of questionnaire responses given by low and high prior knowledge students (in percent)

*Concentration Gradient*

In Overview 1, fixation count results indicated that students with high levels of prior knowledge fixated more in look zone A (M=6.34) than students with low levels of prior
knowledge (M=4.07) (d=-0.85). As the following quote indicates, students with high prior knowledge were able to demonstrate their understanding of how concentration gradient related to the different examples of cell transport processes.

*Interviewer:* Now you mentioned a concentration gradient before. How is this helping you interpret this picture?
*High PK Student:* Uh, this just tells me that there’s a higher concentration inside the cell and obviously [substances] are going to move from a high concentration to a low concentration. So maybe the reason why this is active transport and needs to move [substances] out is because this is a high concentration here. [Substances don’t] normally want to move from a low to a high concentration—they want to move in—which is why the others are passive.
*Interviewer:* So this is passive because it doesn’t take energy and moves substances from high to low concentration and this is active because it takes energy?
*High PK Student:* Yes, because it is kind of going against the flow.

Students with low prior knowledge often did not make these connections with concentration. Many times the interviewer had to prompt these students to determine if they even saw the concentration gradient in the graphic. Some students offered suggestions on how to improve saliency of this feature, either by proximity or color.

*Low PK Student:* Since it was on [the left] side, near this stuff (diffusion graphic) that I didn’t really look at it. It took you pointing that (concentration gradient) out to completely connect it.
*Interviewer:* What can we do to make that better?
*Low PK Student:* I guess just put [the concentration gradient] closer to things you are focusing on—on the one that is different (active transport graphic)…. 
*Interviewer:* So it might have helped if it was on the [right] side of the picture?
*Low PK Student:* Yeah, at least closer to the point you are trying to get across.

*Interviewer:* When you were looking at this picture, did this [concentration gradient] have any meaning to you whatsoever?
*Low PK Student:* I actually didn’t look at that.
*Interviewer:* Why don’t you think you looked at that?
Low PK Student: I don’t know. It is just a similar color to the rest of the picture. It doesn’t really stand out. Also, your eye isn’t drawn to look at words that are written upwards.

The variations in how high and low prior knowledge students understood concentration gradient resulted in differences of eye movement measures between these groups of students in look zone D as well. In the active transport look zone, there were noticeable differences between mean fixation counts of low and high prior knowledge students. High prior knowledge students had a higher mean fixation count (M=9.50) than low prior knowledge students (M=7.14) ($d$=-0.63). Students with high prior knowledge recognized that this look zone was different than the diffusion and passive transport graphics. From their interview responses, it was apparent that they understood these differences to be related to concentration gradient.

High PK Student: The first [arrows] are going from outside to inside and the last [arrow] is going from inside to outside.
Interviewer: OK, so that one’s different because it is going in a different direction?
High PK Student: Yeah, and it needs energy input.
Interviewer: From the picture, does it look like it needs energy input because it is going out of the cell?
High PK Student: Yeah, because it is going to a high concentration.
Interviewer: And how do you know that?
High PK Student: Because of the arrow over here (referring to concentration gradient).

When students with low prior knowledge appeared to recognize a difference between active transport and diffusion/passive transport representations, they were more likely to describe this difference in terms of whether the substances were traveling out of the cell or in to the cell. A few students, however, never even noticed there was a difference in arrow direction with the active transport graphic and offered suggestions to make it more salient.
Low PK Student: The arrows are so thin that this [active transport graphic] was confusing me and I had to look at it for a while. I just thought that it looked the same as [the passive transport graphic] and for this to actually be reversed and the only thing letting you know that was a teeny, tiny arrow…. Interviewer: So what can be done?
Low PK Student: I don’t know, maybe make them fatter.

The graphic selected for classroom instruction, Overview 2, was different from Overview 1, because it made no reference to concentration gradient. However, even without this feature, many students with high prior knowledge (67%) were still able to describe their understanding of simple diffusion, facilitated diffusion, and active transport using the concept of concentration differences appropriately.

High PK Student: Diffusion [is] the passage of molecules through a membrane due to going with the concentration—simply moving through the phosphate heads. Facilitated diffusion is the same except though the membrane via channel proteins. Active transport [is] the passage of molecules through a membrane but energy is needed because it is going against the concentration.

Only 11 percent of students with low prior knowledge were able to explain the differences among the transport processes with an accurate understanding concentration gradient. In some cases, those students who did not make use of concentration gradient in their explanations had other notions about what was occurring.

Low PK Student: Simple diffusion and facilitated diffusion show a lesser amount of blue and red substances going through the bilayer. In active transport, there are more purple substances that can go through the bilayer.

Low PK Student: By the size of the arrows in each picture, I think active [transport] has more particles going through the green blob.

ATP—Energy Input

In Overview 1, mean fixation count results indicated that students with low levels of prior knowledge fixated more in look zone E (M=3.64) than students with high levels of
prior knowledge (M=2.25) (d=0.84). When discussing this section of the graphic, students with low prior knowledge often referred to it as the “yellow p” or “yellow circle,” whereas students with high prior knowledge usually referred to it as “energy” or “ATP.” It appeared that low prior knowledge students found this area of the graphic to be salient, even though they did not understand the underlying concept.

Although low level prior knowledge students fixated more in this zone, as Table 3 indicates, high level prior knowledge students experienced longer average fixation durations (M=0.51) than low level prior knowledge students (M=0.38) (d=-0.82). This result reveals that students with high prior knowledge were attempting to understand the relationship among energy input, active transport, and concentration gradient. Therefore, this section of the graphic was more difficult for these students to process, whereas students with low prior knowledge were not in a position to understand these relationships.

Table 3.
Average fixation duration of low and high prior knowledge students by look zone (in seconds)

<table>
<thead>
<tr>
<th>Look Zone</th>
<th>Low Prior Knowledge</th>
<th>High Prior Knowledge</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-concentration gradient</td>
<td>0.33 (0.09)</td>
<td>0.37 (0.11)</td>
<td>-0.41</td>
</tr>
<tr>
<td>B-diffusion graphic</td>
<td>0.35 (0.09)</td>
<td>0.31 (0.06)</td>
<td>0.45</td>
</tr>
<tr>
<td>C-passive transport graphic</td>
<td>0.33 (0.05)</td>
<td>0.33 (0.06)</td>
<td>-0.02</td>
</tr>
<tr>
<td>D-active transport graphic</td>
<td>0.33 (0.05)</td>
<td>0.34 (0.09)</td>
<td>-0.10</td>
</tr>
<tr>
<td>E-energy input</td>
<td>0.38 (0.08)</td>
<td>0.51 (0.25)</td>
<td>-0.82*</td>
</tr>
<tr>
<td>F-lipid bilayer</td>
<td>0.42 (0.18)</td>
<td>0.43 (0.23)</td>
<td>-0.01</td>
</tr>
<tr>
<td>G-diffusion text</td>
<td>0.33 (0.05)</td>
<td>0.34 (0.07)</td>
<td>-0.02</td>
</tr>
<tr>
<td>H-passive transport text</td>
<td>0.39 (0.18)</td>
<td>0.37 (0.09)</td>
<td>0.17</td>
</tr>
<tr>
<td>I-active transport text</td>
<td>0.36 (0.13)</td>
<td>0.39 (0.27)</td>
<td>-0.17</td>
</tr>
<tr>
<td>J-exocytosis graphic</td>
<td>0.41 (0.11)</td>
<td>0.34 (0.07)</td>
<td>0.81*</td>
</tr>
<tr>
<td>K-endocytosis graphic</td>
<td>0.37 (0.12)</td>
<td>0.34 (0.05)</td>
<td>0.35</td>
</tr>
<tr>
<td>L-exocytosis text</td>
<td>0.44 (0.24)</td>
<td>0.35 (0.15)</td>
<td>0.46</td>
</tr>
<tr>
<td>M-endocytosis text</td>
<td>0.35 (0.12)</td>
<td>0.37 (0.08)</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

* indicates large effect size
In Overview 2, due to the saliency of ATP, both groups of students attempted to use ATP in their explanation of active transport. However, 62 percent of high prior knowledge students correctly explained the role of ATP in the process, compared to only 17 percent of low prior knowledge students.

*High PK Student:* The third graphic shows how energy is required to get molecules through the protein in active transport. Things are moving against the flow.

A few of the students with low prior knowledge did not even mention ATP in their descriptions of active transport and several more misinterpreted the feature.

*Low PK Student:* Active transport is when ATP is pushed in through a [protein] through the membrane

*Low PK Student:* In active transport, the graphic shows how ATP opens up for the particles to go through.

**Endocytosis and Exocytosis**

Endocytosis and exocytosis were additional transport processes represented in Overview 1. In the exocytosis look zone, there were meaningful differences between average fixation durations of low and high prior knowledge students. Low prior knowledge students had a higher average fixation duration (M=0.41) than high prior knowledge students (M=0.34) \((d=0.81)\). The following quotes illustrate the processing difficulties students with low prior knowledge had when interpreting this zone of the graphic. Like the student quoted below, some students completely misunderstood the graphic.

*Low PK Student:* I’m not sure what it is actually, but my guess is that these are water (referring to the particles) and this is the skin (referring to the lipid bilayer)

*Interviewer:* Can you explain what’s going on?

*Low PK Student:* So these are like skin surrounding water or sweat (referring to the vesicles inside the cell), and it moves up to come out of your pores.
Whereas a few students didn’t realize this process was occurring at the cellular level, most students with low prior knowledge recognized the lipid bilayer but had difficulty deciphering the process. The following quotes demonstrate that students quickly noticed the lack of continuity in the exocytosis graphic compared to the endocytosis graphic.

*Low PK Student:* And it seems to me that this [exocytosis graphic] is missing a step. There is something between here (referring to the vesicle touching the lipid bilayer) and here (referring to the vesicle opening up to the outside of the cell). I liked this one (the endocytosis graphic) better than this one (the exocytosis graphic).

*Interviewer:* If you were going to put another step in [the exocytosis graphic], what would it look like?

*Low PK Student:* Probably something more like this [endocytosis graphic]. Probably something about how these connect (referring to the vesicle and the lipid bilayer), because it goes from not connecting at all to having a full fold.

Differences between low and high prior knowledge students were found in the endocytosis look zone as well. Mean fixation count results indicated that students with high levels of prior knowledge fixated more in look zone K ($M=8.91$) than students with low levels of prior knowledge ($M=5.93$) ($d=-0.85$). It is possible that the average fixation duration differences in the exocytosis look zone explain the fixation count differences in the endocytosis look zone; students with low prior knowledge may have fixated in look zone K less as a result of longer fixations in the exocytosis look zone ($J$).

The interviews provided some insight as to why high prior knowledge students had a higher number of fixations in look zone K. As the following quotes indicate, it was apparent that students with high prior knowledge were more apt to make comparisons between the top row of pictures (diffusion/passive transport/active transport) and the bottom row of pictures (exocytosis/endocytosis). Specifically, these students recognized the scaling issues by using the lipid bilayer as their reference.
High PK Student: These [particles] are coming through a different way [in endocytosis] and the cell is actually changing shape and surrounding those [particles]…whereas these [particles in the diffusion graphic] are just coming in through a smaller way.

Interviewer: And do you know why these [particles] are coming in a different way [in endocytosis]? Is the picture communicating that to you?

High PK Student: These [particles entering through endocytosis] are bigger, because this [diffusion graphic] looks like a more zoomed in view and these [exocytosis and endocytosis graphics] look smaller. The cell [in the diffusion graphic] doesn’t have to change shape to take stuff in. These [particles] can fit in the lipid bilayer or proteins in the other pictures.

Interviewer: So although these [particles in the endocytosis graphic] appear to be smaller, you know they are bigger than [the particles in the diffusion graphic].

High PK Student: Uh-huh, because the lipid bilayer is smaller too.

When students with low prior knowledge attempted to make comparisons between the top and bottom rows of graphics, their misinterpretations became apparent. As the interview response reveals, some of the students thought that the diffusion and passive transport representations were zoomed in views of what was occurring on the lipid bilayer of the endocytosis graphic. In other words, these students imagined that if the endocytosis graphic was blown up, they would see particles diffusing across the membrane or proteins allowing particles to pass. Likewise, they had similar explanations relating active transport with exocytosis.

Low PK Student: I’m guessing that that [protein in the passive transport graphic] is right there [in the lipid bilayer of the endocytosis graphic] and it’s letting particles through.

Interviewer: So these pictures down there (referring to endo/exocytosis pictures) relate to the top pictures…specifically these two (diffusion and passive transport) to [endocytosis] because particles are going into the cell.

Low PK Student: Yeah, that makes sense.

A few of the high prior knowledge students were able to predict that other students might not have background knowledge and may incorrectly interpret the relationships between the top
and bottom rows of graphics. The student below offered a suggestion to improve the graphic.

*High PK Student:* I don’t know if you want to do this--this will make it a little more complicated…but to show these [top and bottom graphics] are not the same thing, you might want to put some proteins on the outside [within the membrane of the endo/exocytosis graphics] just to show some similarity between here and here (referring to the top and bottom halves of picture). Because here [in the endocytosis graphic], it looks like this is a cell without any proteins so it must perform this processes (endocytosis) because it can’t do what is shown up here (diffusion/passive transport).

*Interviewer:* So do you think it would be better to have a picture where all [five] of these processes are pictured on the same membrane?

*High PK Student:* Yeah, that might be better. Because then it is all on one cell. If I am not an experienced biology student, I might think…well, some cells might perform different ways and some might have proteins on the outside and some might not…it might be misleading.

**Text Labels and Captions**

Finally, in Overview 1, there were meaningful differences between the mean fixation counts of low and high prior knowledge students in look zone L as well. Students with low levels of prior knowledge fixated more in look zone L (M=1.07) than students with high levels of prior knowledge (M= 0.30) ($d=0.91$). Fourteen of the 20 students with high prior knowledge did not even fixate once in this look zone. One possible explanation for this finding may be that when students with high prior knowledge had fixated in the endocytosis graphic zone, they may have also read the endocytosis text label. Since they have some prior knowledge, when they moved their attention to the exocytosis graphic zone, they may have already suspected the label would say “exocytosis” and did not need to fixate on it.

For both high and low prior knowledge students, average fixation counts continually decreased from the first text look zone (G) to the last text look zone (M). From the eye tracking data and interviews, it seems as if the text labels were not a salient feature for either
high or low prior knowledge students. Instead, students made more use of the graphical components in Overview 1 to interpret cell transport processes.

In Overview 2, when asked what could be done to improve this graphic, low prior knowledge students (72%) were more likely to suggest more labeling and text explanation than high prior knowledge students (33%). Students with low prior knowledge wanted various features of the graphic labeled, including the different particles, the parts of the membrane, the proteins, and the inside and outside of the cell. They also indicated that more explanation of the role of ATP, differences among the particles, and differences among the processes was necessary. On the other hand, high prior knowledge students were less likely to need labels because many of them were already using the terminology fluently. Because they were using terms like “proteins” and “phosphate heads,” describing the different particles in terms of size, shape, and color, and using concentration gradient in their explanations, the addition of labels for could prove to be more distracting for these students.

Discussion

The results of this study revealed differences in how students with low and high levels of prior knowledge viewed and interpreted graphics of cellular transport. As supported by fixation count results, the most salient features for students with low prior knowledge were look zones that made use of bright or contrasting colors. Low prior knowledge students had higher fixation counts on the proteins, the ATP, and the particles crossing the membrane, however interview and questionnaire responses indicated that they were not able to understand these features at a deeper level. For example, these students noticed the color and shape differences of the particles, but did not have the background knowledge to know that those differences were indicating that some particles were lipid-soluble and some particles
were water-soluble. Likewise, the color prompted students to look at the ATP, but did not provide enough information for students to understand the role of energy in the process of active transport.

In this study, color highlighted certain features in the graphics and attracted student attention. Even though students with low prior knowledge were unable to understand the underlying content material, at least they fixated on relevant features of the graphic. On the other hand, when important features were not emphasized, as was the case with the concentration gradient and active transport look zones, students with low prior knowledge overlooked these features and their importance in understanding the graphic. Color cannot communicate conceptual understanding, but at least learners have a better chance of extracting relevant information from the graphic when their attention is cued to the parts of the graphic that would be most helpful in their interpretation.

The differences found between students with low and high prior knowledge are best explained with Schnotz and Bannert’s integrative model of text and picture comprehension (Schnotz, 2002; Schnotz & Bannert, 2003). This model provides insight into how learners process graphics through the construction of multiple mental representations. Initially, the graphic is processed at a perceptual level, creating a visual mental model of surface structures. Then, learners begin to construct a more comprehensive mental model where the surface level interpretation is linked to a higher level conceptual understanding of the material. This mental model is more abstract and irrelevant perceptual information is omitted. Students with low prior knowledge often fail to make it to this second level; their internal representation remains at the surface level.
In this study, because low prior knowledge students had fragmented and weakly connected background knowledge, they focused on the superficial features of the graphic to build an understanding of the concepts represented (Seufert, 2003). Students with low prior knowledge could decipher that the graphics were trying to communicate basic differences among cellular transport processes, but their interpretations did not go beyond surface level processing (such as color differences of particles, direction of particle travel, and particle travel through the lipid bilayer versus proteins). As opposed to high prior knowledge students, these students did not have the background knowledge to make the connections between the salient features they viewed and underlying content principles.

Low prior knowledge students can become easily confused when the most salient features of a display are not the most relevant or important for interpreting the graphics or, as in this case, when the features of the graphic most pertinent for conceptual understanding are not made salient (Linn, 2003). Students were not cued to look at the concentration gradient look zone, therefore many made no use of this important theme in their explanations of the differences between diffusion, passive transport, and active transport. Unlike students with high prior knowledge, they were unable to see that multiple representations with different surface features can be explained with the same underlying concept.

On the other hand, high prior knowledge students had more abundant background knowledge to understand the important content principles represented by the graphic; they possessed a large number of schemas specific to the domain that were organized and easily accessible when needed (Chi, Glaser, & Rees, 1982). Schemas hold a large amount of information, yet because they are processed as a single unit in working memory, they are less likely to cause overload (Kirschner, 2002). For these reasons, students with high prior
knowledge were able to attend to different information than those with low prior knowledge (Chi, Feltovich, & Glaser, 1981); they were able to encode the thematically relevant features of the graphic, not just the perceptually salient features.

Students with high prior knowledge were able to go beyond the surface level processing experienced by low prior knowledge students. With more background knowledge about the subject, these students used differences in particle color, direction of particle travel, and whether the particles passed through the lipid bilayer versus proteins to develop a more sophisticated understanding of the differences among cellular transport processes. This understanding of the core principles related to cellular transport could explain why high level prior knowledge students were less likely to suggest the need for more text in the form of labels and captions. Also, these students were better able to make connections among the different processes represented. For example, students with high prior knowledge made more attempts to relate the processes represented at the bottom of Overview 1 (exo/endocytosis) with the processes represented at the top (diffusion, passive transport, and active transport).

Although the importance of visual representations in science education has been established, more research is necessary on how to best facilitate learning with graphics for students with varying amounts of prior knowledge. Visual representations are important resources in the communication of scientific concepts and can improve conceptual understanding; however, students may have more difficulty understanding graphics than initially assumed (Wu, Krajcik, & Soloway, 2001). Graphics that are thought to promote active cognitive processing may be useless if the learner does not receive the information in
the manner intended. Therefore, the questions asked in this study can offer a more complete understanding of how these learners view and interpret graphics.

Ultimately, these findings could be used to design visual representations to meet the needs of differentially prepared students. For low prior knowledge students in particular, the results suggest the need for scaffolding within graphics by cueing student attention to the thematically relevant features. In addition, many of these students require instructional guidance in the form of captions or teacher explanation in order to construct conceptual understandings that would otherwise be out of reach (Pozzer-Ardenghi & Roth, 2005). On the other hand, the findings suggest experts may not need instructional guidance because they already possess internal guidance in the form of schemas (Kalyuga et al., 2003). In fact, instructional guidance has the potential to impede conceptual understanding if it provides overly redundant information.
References


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The Influence of Prior Knowledge on Viewing and Interpreting Graphics with Macroscopic and Molecular Representations
Abstract

In the science classroom, learners are faced with multiple representations of information. Specifically, in cellular transport instruction, phenomena are represented at both the macroscopic and molecular level. Previous research has indicated that the use of multiple representations with macroscopic and molecular features can improve conceptual understanding; however, the influence of prior knowledge of the domain cannot be overlooked. This study represents one part of a larger research project designed to examine how prior knowledge influences how high school students ($n=54$) view and interpret graphic representations of cellular transport processes. Using eye tracking technology and sequential analysis, this study investigated how students with different levels of prior knowledge transitioned among the macroscopic and molecular representations of the selected graphics. The results indicated that high prior knowledge students transitioned more frequently between the molecular representations, whereas low prior knowledge students transitioned more frequently between the macroscopic representations. These findings suggest that students with high prior knowledge distributed their visual attention on conceptually relevant features, while low prior knowledge students focused on surface features. In addition, low prior knowledge students transitioned more frequently between macroscopic and molecular representations, suggesting that these students were experiencing more difficulty as they were coordinating the representations. Because these students were using surface features to create linkages between the macroscopic and molecular representations, they were unable to understand the underlying themes of the graphic. More research on the differences in the
distribution of visual attention among learners can provide further insight as to the
difficulties low prior knowledge students face when interpreting multiple representations.
The Influence of Prior Knowledge on Viewing and Interpreting Graphics with Macroscopic and Molecular Representations

Introduction

Research on visual representations has received a great deal of attention in the science education literature (Hegarty, Carpenter, & Just, 1991; Mathewson, 1999; Mayer & Anderson, 1991; Pozzer-Ardenghi & Roth, 2005). Specifically, considerable attention has been devoted to the role of representations on acquiring knowledge and understanding relationships and processes in science courses (Mandl & Levin, 1989). Students are commonly exposed to visual displays of information in textbooks, teacher presentations, and computer-based multimedia materials. For example, in a survey of six science textbooks, Mayer (1993) found that 55% of the printed space was accounted for by illustrations. Since the science classroom is saturated with representations of scientific concepts, the ability of students to interpret and understand these representations has become increasingly important in education (Ferk et al. 2003).

Multiple Representations

Almost every learning situation involves representing information in different forms (van Someren et al., 1998). With typical instructional media, learners are faced with multiple representations of information. Multiple representations function to support student learning in a variety of ways. First, they can complement one another with regard to information and processes. For instance, when a single representation cannot convey all of the information needed about the domain, using multiple representations that transmit different pieces of information could prove helpful. On the other hand, if the information presented in one
representation is presented in the other, the representations may be similar to one another in
terms of their usefulness. In this case, the representations support complementary processes
(Ainswoth, Bibby, & Wood, 1998). Multiple representations can also constrain the
interpretation of abstract concepts. More specifically, a second representation may be used
to support learners as they interpret a more complicated, abstract representation (Tsui &
Treagust, 2003). Finally, multiple representations can facilitate the integration of
information and the construction of deeper understandings. By providing rich
representations, learners can perceive complex ideas in a novel way and develop an
understanding of the underlying principles of the domain (Ainsworth, 1999).

It is possible for multiple representations in a learning task to fulfill all of these
functions simultaneously. However, regardless of the function of multiple representations,
they require coherence formation for complete understanding (Seufert, 2003); learners must
be able to combine multiple representations into an integrated knowledge structure. To make
connections across multiple representations, initially learners must understand the format of
each representation and select the most relevant aspects for further processing. Next, the
learner begins to relate each representation to the domain it represents; for each
representation, internal connections will be made among the aspects selected for processing
to create a separate mental model. Finally, the resulting mental representations will be
integrated into a more abstract model that incorporates them both (Ainsworth, Bibby, &
Wood, 1998; Mayer, 1999; van Someren et al., 1998). Learners will create referential
connections between the corresponding features of the different representations, by mapping
the knowledge from one representation onto that of another representation (Seufert, 2003).
**Macroscopic and Molecular Representations**

Research on multiple representations has been of particular interest in the area of chemistry (Kozma, 2003; Kozma & Russell, 1997; Rohr & Reimann, 1998; Treagust, Chittleborough, & Mamiala, 2002; Wu, Krajcik, & Soloway, 2001). Visual representations play a critical role in chemistry, where complex concepts are not always directly observable (Kozma, 2000). Chemical phenomena are represented on three levels—macroscopic, molecular, and symbolic (Johnstone, 1993). Macroscopic representations depict observable phenomena, while molecular and symbolic representations describe invisible and abstract concepts. Molecular representations illustrate chemical processes by the arrangement and movement of molecules, whereas symbolic representations present formulas, equations, and structures (Wu, Krajcik, & Soloway, 2001).

A number of studies related to different chemistry topics have shown that the simultaneous display of molecular representations corresponding to observable phenomena on the macroscopic level improves conceptual understanding of the domain. In one such study, students were provided worksheets and instruction that highlighted the particulate nature of matter related to three different topics—states of matter, bonding and solutions, and stoichiometry (Bunce & Gabel, 2002). Compared with the control group, this emphasis on the particulate nature of matter led to significantly higher scores on molecular questions as well as overall achievement tests. Russell and Kozma (1994) explored 4M: Chem, a visualization tool that allowed for simultaneous macroscopic and molecular views on gaseous equilibrium. By comparing pre-and post-test scores, students using this tool increased their understanding of equilibrium and experienced a decrease in misconceptions. In a study by Ardac and Akaygun (2004), some students received chemical change
instruction that emphasized concepts at the molecular level; these students were shown to outperform students receiving regular instruction on post-test scores.

Sanger and his colleagues have conducted a number of studies in this area. In a study involving students’ conceptions of pure substances and mixtures, students who received molecular instruction were better able to answer conceptual questions at the molecular level (Sanger, 2000). Regarding the topic of electrochemical cells, Sanger and Greenbowe (1997) reported that students viewing molecular level computer animations were less likely to demonstrate the misconception that electrons flow in aqueous solutions without the assistance of ions than students who did not. Finally, Sanger and his colleagues showed some students animations illustrating the molecular processes of diffusion of perfume molecules in air and osmosis through a selectively permeable membrane. Students who viewed these animations were less likely to exhibit misconceptions regarding equilibrium and less likely to have anthropomorphic views of matter (Sanger, Brechreisen, & Hynek, 2001).

**Expert and Novice Differences**

In general, the results have been promising; the inclusion of molecular representations can improve both macroscopic and molecular understandings. However, much of the research also indicates that the influence of domain knowledge cannot be overlooked (Kozma, 2003; Kozma & Russell, 1997; Wu, Krajcik, & Soloway, 2001; Wu & Shah, 2004). Learning from multiple representations at the macroscopic and molecular level can be a difficult process, especially for novices. Novices have little or no knowledge of the domain; what knowledge they do have is stored in small chunks and only weakly connected (diSessa, 1993). Novices depend heavily on observable phenomena to construct understandings
(Seufert, 2003); therefore, in many cases, they rely predominantly on macroscopic representations and make few links across macroscopic and molecular representations.

If novices do attempt to coordinate macroscopic and molecular representations, they often experience problems in identifying conceptually relevant features (Kozma, 2000). Students with little domain knowledge generally focus on surface features to make links across representations. However, little about surface features is related to the underlying themes of the representations (Wu, Krajcik, & Soloway, 2001). Because they have difficulty finding more abstract similarities across representations, novices are misled by surface similarities among macroscopic and molecular representations. They misrepresent the graphics and fail to construct a meaningful understanding.

On the other hand, experts with domain experience have larger chunks of information built up in a hierarchically organized framework (van Someren et al., 1998). When experts are faced with multiple representations of macroscopic and molecular knowledge, they are able to use conceptually relevant themes to coordinate across the representations (Kozma, 2003). These learners are not distracted by surface features; they realize that even with different surface features, the macroscopic and molecular representations are depicting the same underlying concepts. Experts are able to construct a deeper, more abstract understanding of the representations (Seufert, 2003).

Rationale and Research Questions

Much of the research on macroscopic and molecular representations has been in the area of chemistry; very few studies have been conducted in other content areas. In this study, diffusion and osmosis representations were selected because they also require visualization of macroscopic and molecular phenomena (Friedler, Amir, & Tamir, 1987; Johnstone &
Diffusion and osmosis are important in understanding many life processes (Odom & Barrow, 1995), yet are difficult topics for students at all levels to comprehend. Both processes are observable at the macroscopic/microscopic level; however students often are unable to grasp the molecular concepts necessary for complete understanding (Westbrook & Marek, 1991).

This study represents one part of a larger research project designed to examine how prior knowledge influences how high school students view and interpret graphic representations of cellular transport processes. Using eye tracking technology, this study investigated how students with different levels of prior knowledge transitioned among the macroscopic and molecular representations of the selected graphics. In addition, by complementing eye tracking data with interview responses, this research examined how students with high and low levels of prior knowledge interpreted meaning from these graphics with both macroscopic and molecular representations. In this study, we were concerned with how frequently high and low prior knowledge students transitioned from molecular to molecular features (MOL-MOL), macroscopic to macroscopic (MAC-MAC) features, and macroscopic to molecular features (MAC-MOL, but also included transitions in the other direction from molecular to macroscopic features).

From previous research, we expected to see differences in how students with more or less domain knowledge of the topic transitioned between the macroscopic and molecular representations. Specifically, we hypothesized that students with high prior knowledge would make more MOL-MOL transitions as they viewed the graphics. Because high prior knowledge students have a deeper, more abstract understanding of the topic (Kozma, 2003) as well as the ability to quickly establish connections between the external representations
and their internal models (Chi, Feltovich, & Glaser, 1981), they are more likely to benefit from molecular representations. Therefore, MOL-MOL transitions were predicted to be the most helpful to these students in understanding the underlying themes of the graphic. On the other hand, low prior knowledge students with little domain knowledge depend on observable phenomena (Seufert, 2003). Because their thinking relies heavily on sensory information and they are less able to understand the abstract, molecular representations (Wu, Krajcik, & Soloway, 2001), we anticipated that low prior knowledge students would make more MAC-MAC transitions. Finally, we predicted that both low and high prior knowledge students will attempt to make linkages between MAC-MOL representations. However, because of the heavy reliance on surface features for students with low prior knowledge, their linkages are superficial and unrelated to the content of the representations (Kozma & Russell, 1997). Therefore, we hypothesized that low prior knowledge students would transition more frequently between MAC-MOL features, since the connections they attempt are not facilitating their conceptual understanding.

Efforts to understand how learners integrate and construct understanding from multiple representations are not new; however, much of the research has focused on testing knowledge gains to measure student understanding of macroscopic and molecular representations. Although analyzing summative information is helpful, it is also important to study how learners are acquiring information from the representations to provide a more complete understanding of the topic. Researching how students view graphics with macroscopic and molecular representations can offer insight as to whether visual attention distribution accounts for some of the differences in understanding presented in the literature.
Also, this methodology has the potential to reveal patterns in how students view multiple representations; these patterns could be used to inform instructional design.

Methodology

Prior Knowledge Assessment

The participants in this study were 54 high school seniors enrolled in Advanced Placement Biology. All students had previously taken biology and chemistry at the high school level. The prior knowledge of students related to cellular transport was assessed using a modified version of the Diffusion and Osmosis Diagnostic Test (Odom & Barrow, 1995). As originally developed, the DODT is a 24-question, two-tier multiple choice instrument. The first question of the pair is a content question; the second question is a justification question, requiring students to give a reason for their first response. Six additional items were created and piloted with two other groups of high school students to increase the scope and depth of the instrument. The main topic areas assessed by the modified DODT included the particulate and random nature of matter, concentration and tonicity, kinetic energy of matter, membranes, and the processes of diffusion and osmosis.

Students could receive a maximum score of 45 on the 30-item DODT. Because first-and second-tier questions differed in terms of difficulty level, correct responses on these questions received different point values. A correct response on a first-tier content item received one point; a correct response on a second-tier justification item received two points. To assure students were not rewarded for merely guessing, students were not given points for a correct second-tier response unless they correctly answered the first-tier item. To differentiate high and low prior knowledge learners, students were divided into three groups based upon their scores on the DODT. Due to small sample sizes, the top-third (high prior
knowledge) and bottom-third (low prior knowledge) groups were compared using effect size
(Cohen, 1988) to assure meaningful differences in prior knowledge between the groups.
Students in the middle-third group were not analyzed in this study.

With a score of 45 possible, scores of the 54 participants on the DODT ranged from
11-39 (M = 24.1). The top- (n = 20) and bottom-third (n = 16) groups were compared to
determine if meaningful differences existed. Students with the highest scores on the DODT
(M = 31.2, ranging from 28-39) showed large differences when compared to students with
the lowest scores (M = 16.7, ranging from 11-20) (d = -1.18).

*Eye Tracking*

Data were collected on eye movement measures to provide a view of how students
with differing levels of domain knowledge acquire information from graphic representations.
By providing a direct measure of how visual attention is allocated, eye tracking was used to
determine how students with different levels of prior knowledge transition among the
macroscopic and molecular representations in diffusion and osmosis graphics. The Applied
Science Laboratory (ASL) model 504, a video-based combined pupil and corneal reflection
eye-tracker, was used to collect eye movement measures. Two cell transport graphics with
both macroscopic and molecular features were selected for analysis: Diffusion (Figure 1) and
Osmosis (Figure 2). (In the Osmosis graphic, the beakers containing cells of various sizes
were considered to be macroscopic representations, because they were depicting observable
changes in the cells). Participants viewed each graphic for 35 seconds.
Figure 1. Diffusion graphic with look zones defined (A-I).

Figure 2. Osmosis graphic with look zones defined (A-I).
(Property of R.F. Baker, USC Medical School)
The eye tracking system collected data 60 times per second on the gaze direction of the left pupil relative to the computer screen. Calculations using these data allowed points of perceptual fixation on the computer screen to be determined. Fixations occur when a subject’s gaze is stabilized over an area of interest for at least 200 milliseconds (Duchowski, 2002). Fixations from one area to another are separated by saccades, or the “jumps” between fixations. The literature indicates that learners fixate on features that are salient, interesting, or important through experience (Goldberg & Kotval, 1999; Henderson, 1992). In this study, look zones were defined around these features of interest in the graphic (refer to Figures 1 and 2), and fixations were recorded within these look zones.

A sequential analysis of fixations was conducted for this research using a lag sequential model. Although commonly used to study dependency relationships in multivariate observational data, the lag sequential model can be applied to any research where categorical event sequences can be measured. The basic premise of sequential analysis is the examination of whether particular transitions between events occur more or less frequently than would be expected by chance (Sackett, 1979). The observed transition frequency from one look zone (criterion event) to the next look zone (target event) in a graphic was calculated and compared to the expected transition frequency for this same 2-event sequence by means of z score (Allison & Liker, 1982; Bakeman & Gottman, 1997). Following the z score distribution for the normal curve for one-tailed tests of significance, a z score of 1.65 or higher is at a significance level of \( p < 0.05 \), a z score of 2.33 or higher is at a significance level of \( p < 0.01 \), and a z score of 3.11 or higher is at a significance level of \( p < 0.001 \) (Pagano, 1990). A positive or negative sign indicates whether the transition occurred more or less frequently than chance would predict.
In this study, the data were pooled across subjects with low prior knowledge and subjects with high prior knowledge to increase the reliability of this summary statistic. Given the large number of look zone to look zone comparisons possible in the graphics, the number of 2-event sequences analyzed was reduced to relevant research questions. Specifically, this study analyzed the lag 1 transition frequencies between MOL-MOL, MAC-MOL, and MAC-MAC features for high and low prior knowledge learners. Even still, to further reduce type I error, only those MOL-MOL, MAC-MOL, and MAC-MAC transitions considered to be helpful in making sense of the graphic were analyzed. Only MOL-MOL and MAC-MAC representations that were directly adjacent to one another were examined in this study. For example in the diffusion graphic, a MOL-MOL transition between look zones A and B was considered important for analysis, while a MOL-MOL transition between look zones A and D was not. Likewise, only MAC-MOL representations that directly corresponded to one another were analyzed. Because the sequential analysis of each graphic included 22 z score assessments, the Bonferroni corrected alpha was set for 0.002. Therefore, z scores higher than 2.88 indicate the 2-event sequence was observed more frequently than expected. The resulting z scores of high and low prior knowledge learners will be compared to ascertain how these groups of students with different domain knowledge transition between molecular and macroscopic look zones.

Interviews

Immediately following eye tracking, interviews were conducted to determine how students with high and low levels of prior knowledge interpret graphics with both macroscopic and molecular graphic representations. Combining eye tracking data with interviews has been shown to be effective in numerous studies (Mackworth & Morandi,
1967; Patrick, Carter, & Wiebe, 2005; von Keitz, 1988). Whereas eye tracking can provide a direct view of how learners visually attend to graphics with multiple representations, interview responses can indicate if students are able to understand what the macroscopic and molecular representations are intending to convey. The specific questions asked depended on the graphic, but in general students were asked the following questions:

1. Describe the most obvious features of this graphic.
2. Explain what you think this graphic is trying to communicate.
3. What suggestions do you have to improve this graphic?

Responses from the students were used to complement the eye tracking data. For example, findings related to how frequently students transitioned between MOL-MOL, MAC-MOL, and MAC-MAC features were explained by interview responses from high and low prior knowledge students.

Results

The z score values of high and low prior knowledge students for both graphics are reported in Table 1. This section summarizes the findings resulting from the sequential analysis of eye fixation data. In addition, these differences found in MOL-MOL, MAC-MOL, and MAC-MAC transitions between high and low prior knowledge learners are explained with interview responses from these students.
Table 1.  
*Comparison of z-score values of high and low prior knowledge learners from Diffusion and Osmosis graphics*

<table>
<thead>
<tr>
<th>2-event sequence</th>
<th>Diffusion Graphic</th>
<th>Osmosis Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High PK</td>
<td>Low PK</td>
</tr>
<tr>
<td>MOL-MOL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A—B</td>
<td>2.04</td>
<td>0.81</td>
</tr>
<tr>
<td>B—A</td>
<td>3.06*</td>
<td>3.31*</td>
</tr>
<tr>
<td>C—D</td>
<td>1.53</td>
<td>2.90*</td>
</tr>
<tr>
<td>D—C</td>
<td>3.90*</td>
<td>5.39*</td>
</tr>
<tr>
<td>E—F</td>
<td>4.15*</td>
<td>5.96*</td>
</tr>
<tr>
<td>F—E</td>
<td>3.05*</td>
<td>3.69*</td>
</tr>
<tr>
<td>MAC-MOL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A—G</td>
<td>0.64</td>
<td>2.97*</td>
</tr>
<tr>
<td>G—A</td>
<td>-1.47</td>
<td>-1.08</td>
</tr>
<tr>
<td>B—G</td>
<td>3.05*</td>
<td>3.45*</td>
</tr>
<tr>
<td>G—B</td>
<td>0.02</td>
<td>3.11*</td>
</tr>
<tr>
<td>C—H</td>
<td>-0.25</td>
<td>2.99*</td>
</tr>
<tr>
<td>H—C</td>
<td>-2.97</td>
<td>-1.82</td>
</tr>
<tr>
<td>D—H</td>
<td>-2.24</td>
<td>-1.88</td>
</tr>
<tr>
<td>H—D</td>
<td>0.30</td>
<td>3.04*</td>
</tr>
<tr>
<td>E—I</td>
<td>1.82</td>
<td>2.99*</td>
</tr>
<tr>
<td>I—E</td>
<td>3.12*</td>
<td>3.28*</td>
</tr>
<tr>
<td>F—I</td>
<td>0.48</td>
<td>2.88*</td>
</tr>
<tr>
<td>I—F</td>
<td>0.95</td>
<td>-1.10</td>
</tr>
<tr>
<td>MAC-MAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G—H</td>
<td>3.54*</td>
<td>4.50*</td>
</tr>
<tr>
<td>H—G</td>
<td>0.95</td>
<td>2.93*</td>
</tr>
<tr>
<td>H—I</td>
<td>4.72*</td>
<td>4.84*</td>
</tr>
<tr>
<td>I—H</td>
<td>1.93</td>
<td>2.95*</td>
</tr>
</tbody>
</table>

With Bonferroni correction, significant $z = 2.88, p = 0.002$ (indicated with *)

*MOL-MOL Sequences*

*Diffusion Graphic*

For most of the MOL-MOL sequences, z scores of both high and low prior knowledge learners were significant. Of the six MOL-MOL transitions analyzed, there were two sequences (A—B, $z = 2.04$ and C—D, $z = 1.53$) for high prior knowledge learners and one sequence (A—B, $z = 0.81$) for low prior knowledge learners where the observed transition frequency was no more than expected by chance. Although it was hypothesized that high prior knowledge learners would transition more frequently between MOL-MOL
representations, the sequential analysis findings from this graphic do not support this assertion. In fact, for all MOL-MOL transitions except A—B, the $z$ scores for low prior knowledge learners were higher than those of high prior knowledge learners.

One explanation for this finding is due to the complexity of the molecular representations in this particular graphic. The molecular representations in this graphic depict water molecules, sugar molecules, and large molecules on either side of the selectively permeable membrane, and are more complicated than the molecular representations in the Osmosis graphic. Consequently, low prior knowledge students required more frequent transitions between these molecular features in an effort to make sense of them. In the interviews, these students struggled to explain which molecules were crossing the membrane and in what direction. In addition to making more MOL-MOL transitions, students with low prior knowledge more frequently transitioned between molecular features in both directions (i.e. C—D, $z = 2.90$ and D—C, $z = 5.39$), whereas high prior knowledge students were more prone to experience a significant number of transitions one way (D—C, $z = 3.90$) but not the other (C—D, $z = 1.53$).

_Osmosis Graphic_

The MOL-MOL sequential analysis results for this graphic were remarkably different compared with the Diffusion graphic. High prior knowledge students transitioned more frequently than expected between the MOL-MOL representations of this graphic. The $z$ scores of high prior knowledge learners were significant and higher than the $z$ scores of low prior knowledge learners for all six MOL-MOL sequences; in contrast, the $z$ scores of low prior knowledge learners only reached significance for the A—B sequence ($z = 4.81$) and the C—D sequence ($z = 3.31$). Interview responses indicated that low prior knowledge students
may have found the molecular representations in this graphic to be deceptively simple. Many low prior knowledge students seemed confident in their interpretations of the molecular representations; however, over half of them explained the movement of molecules incorrectly. These students responded that the green molecules were crossing the membrane, even if they recognized the blue molecules to be water.

*Interviewer:* What is going on in [the top pictures]?
*Low PK Student:* In the first picture, nothing is moving. In [the second] one, the green dots are moving outside of the cell and the cell is getting smaller. The opposite is happening [in the third picture].

*Interviewer:* How do you know the “green things” are moving?  
*Low PK Student:* Because the arrow shows them going out.

The explanation that low prior knowledge students assumed they understood the molecular representations is also supported by the sequential analysis data. The $z$ scores of low prior knowledge students for the sequences were not significant in both directions, as they were for the Diffusion graphic. In addition, neither of the $z$ scores from E—F ($z = 1.73$) and F—E ($z = 0.30$) were significant for low prior knowledge learners. These finding may indicate that by the time these learners reached the right side of the graphic (as most read images from left to right), they had already assumed they understood the molecular representations. On the other hand, high prior knowledge students transitioned in both directions between the molecular representations to a level of significance. The interview responses from these students indicated that were grappling with some of the more subtle issues of the representations. Many high prior knowledge students experienced difficulty understanding the membrane curvature and molecular movement.

*High PK Student:* The curve is throwing me off.  
*Interviewer:* What do you mean?  
*High PK Student:* Well, it seems like one of them is not going the right way.
Interviewer: Do you know which one?
High PK Student: I think [the one on the right] should be curved the other way.
Interviewer: Why is that?
High PK Student: Because the water is moving from outside to in.

Interviewer: Is there anything we can do to improve this graphic?
High PK Student: I don’t know. At first I had trouble figuring out which substance went through the membrane. Because it almost looks like the green is going through [the membrane], but it’s the blue. It took me a while to get it.
Interviewer: How could we make that easier to understand?
High PK Student: Well, now I notice [the arrow] is blue, but I didn’t see it at first. Maybe if you had a bunch of arrows coming from the water molecules….

MAC-MOL Sequences

Diffusion Graphic

Low prior knowledge students transitioned more frequently between the MAC-MOL representations in all cases except I—F ($z = -1.10$). Not only did low prior knowledge students transition more frequently between these representations, but more of their transitions were at a level of significance. These students had eight transition sequences with $z$ scores at a level of significance compared with only two transition sequences for high prior knowledge students (B—G, $z = 3.05$; I—E, $z = 3.12$). Students with high prior knowledge did not have to transition as frequently between the macroscopic and molecular features to understand the connections between the two different representations. As the findings support, they did not need transitions in both directions to accurately understand the relationships between the features. For example, of the four possible sequences tested among look zones A, B, and G, high prior knowledge students had only one transition at a level of significance (B—G, $z = 3.05$). With regard to the four possible sequences tested among look
zones C, D, and H, none of these transitions were significant for students with high prior knowledge.

As the following interview response illustrates, even with few significant transition sequences, high prior knowledge students made accurate connections between the macroscopic and molecular representations and were able to notice subtleties that eluded students with low prior knowledge.

*Interviewer*: Can we do anything to improve this graphic?

*High PK Student*: This is small and well…the color in the bag doesn’t match the color up here.

*Interviewer*: You mean one is purple and one is red?

*High PK Student*: Yeah, it’s not that big of a deal, but I would fix it.

Where as high prior knowledge students needed few transitions at a level of significance to decipher the relationship between the macroscopic and molecular features, low prior knowledge students had more transition sequences that were significant in both directions (ex. B—G and G—B). If the students’ transitions were not significant in both directions, the molecular to macroscopic sequence was more likely to be significant than the macroscopic to molecular transition.

*Osmosis Graphic*

Although low prior knowledge students experienced more MAC-MOL transitions in general, the results for this graphic indicate that students with high prior knowledge made more frequent MAC-MOL transitions when compared with the Diffusion graphic. In this graphic, there were five transition sequences (B—G, G—B, H—C, H—D, F—I) where high prior knowledge students had higher z scores than low prior knowledge students compared to only one in the Diffusion graphic. In addition, students with high prior knowledge had five MAC-MOL transitions higher than expected by chance (A—G, z = 3.09; H—C, z = 3.00;
H—D, $z = 3.07$; E—I, $z = 2.98$; F—I $z = 3.84$), compared to only two in the Diffusion graphic. On the other hand, low prior knowledge students had eight transition sequences that were significant. The high transition frequency of high prior knowledge students can be explained by the interview responses. Many of these students indicated that the discrepancy in time between the macroscopic and molecular representations made these connections more difficult to interpret.

*Interviewer:* And how does that (referring to the shrinking cell) relate to what is going on in the picture above it?

*High PK Student:* Well [the molecular picture] is a blow up of [the macroscopic picture]. No, it is but it isn’t. It should have more blue particles over here [on the outside of the cell]. But it hasn’t happened yet.

This discrepancy could also explain why high prior knowledge students had two transition sequences at a level of significance for the hypertonic (H—C, $z = 3.00$; H—D, $z = 3.07$) and hypertonic representations (E—I, $z = 2.98$; F—I $z = 3.84$), but only one transition sequence at a level of significance for the isotonic representations (A—G, $z = 3.09$). The mismatch in time between the macroscopic and molecular features was not an issue in the isotonic representations, and could explain why high prior knowledge had fewer sequences at a level of significance.

*MAC-MAC Sequences*

*Diffusion Graphic*

For all MAC-MAC sequences tested, low prior knowledge students transitioned more frequently between these features than high prior knowledge students. In addition, all transition sequences were significant for students with low prior knowledge, whereas only two were at a level of significance for high prior knowledge students (G—H, $z = 3.54$; H—I, $z = 4.72$). The interview responses also supported that the observable phenomena were more
helpful to low prior knowledge students attempting to interpret the underlying content of these representations. Low prior knowledge students predominately used the color change in the bags to summarize what was taking place in this graphic. Although high prior knowledge students were more apt to explain this graphic in terms of the movement of sugar molecules, they discussed the color change in the bags as well. The interview responses also seem to indicate that high prior knowledge students may have transitioned more between MAC-MAC features of this graphic because they represent a change in the beakers over time. However, even as students with high prior knowledge transitioned between MAC-MAC features, only transitions in one direction were significant (ex. G—H, z = 3.54; H—G, z = 0.95).

**Osmosis Graphic**

Similar to the Diffusion graphic, low prior knowledge students transitioned more frequently between MAC-MAC representations than high prior knowledge students in three of the 4 sequences tested in this graphic (G—H, H—G, and H—I). Likewise, students with low prior knowledge had more transition sequences at a level of significance; three transition sequences were significant for low prior knowledge learners (G—H, z = 3.18; H—I, z = 3.14; I—H, z = 2.89) while only one transition sequence was significant for high prior knowledge learners (I—H, z = 3.85). When low prior knowledge students were asked what the graphic was communicating, almost all of them began with an explanation of the different cell sizes in the macroscopic representations. High prior knowledge students were more likely to begin by explaining the graphic in terms of molecular movement of water. The interview responses also indicate that high prior knowledge students may have had a significant number of transitions from I—H due to the color change of the solution in the hypotonic beaker.
High PK Student: I didn’t know why these two [on the left and in the middle] had the same colored-water and that one [on the right] is blue.  
Interviewer: Is that communicating something to you?  
High PK Student: At first I thought it was confusing because I thought this [beaker in the middle] should have blue water too. But I think [the middle picture] is trying to show it’s green because it is salt water and this one [on the right] is blue because it is fresh water.

Discussion

Overall, the results of this study provide support for the hypothesis. In general, high prior knowledge students transitioned more frequently between MOL-MOL representations. Because these students have more domain knowledge, it is assumed that molecular representations were more helpful in conceptual understanding. Although in most cases low prior knowledge students transitioned less between MOL-MOL features, this trend seemed to depend on the perceived complexity of the representations. The molecular representations in the Osmosis graphic appeared deceptively simple. It was relatively easy for students to pick out the relative amounts of green and blue molecules on either side of the membrane. It is likely that students with low prior knowledge had a relatively easy time constructing a mental model of the surface features (green and blue molecules), and therefore they may have assumed they understood the underlying concepts presented. However, in the Diffusion graphic, the molecular features were more complex in terms of number and shapes of molecules represented. Deciphering which molecules were moving across the membrane required more effort from inexperienced learners. In this case, low prior knowledge students may have transitioned more between MOL-MOL representations to construct an understanding of the surface features, whereas high prior knowledge students were able to chunk information and easily compare the molecules on one side of the membrane with the other. Therefore, the results seemed to indicate that when low prior knowledge students are
having difficulty understanding the representations at a surface level, more MOL-MOL transitions can be expected.

Low prior knowledge students transitioned more frequently between the MAC-MOL representations in both graphics. It is believed that students with less domain knowledge experience more difficulty forming linkages across the different representational levels (Kozma, 2000). These students appeared to transition more between MAC-MOL features because they were attempting to map the surface features of one representation on to another. For example, in the Diffusion graphic, low prior knowledge students recognized the color change in the macroscopic representations. It is likely that these learners were trying to relate this color change on the macroscopic level to the colors of the molecules at the molecular level. Unfortunately, in this case, the color change at the macroscopic level did not correspond to any of the molecule colors at the molecular level. Because low prior knowledge students have difficulties mapping the underlying content of one representation to another, they relied heavily on surface features which may not be easily coordinated between the macroscopic and molecular levels. On the other hand, high prior knowledge students required fewer transitions between MAC-MOL features to construct an integrated understanding of the representations. High prior knowledge students used underlying scientific themes, not surface features, to coordinate their mental models of the macroscopic and molecular representations. As the results indicate, more frequent transitions between MAC-MOL representations were recorded only when discrepancies between the macroscopic and molecular representations impeded coordination.

Low prior knowledge students also transitioned more frequently between MAC-MAC representations. This result was expected since these students have a tendency to rely more
heavily on observable phenomena. In general, high prior knowledge students did not make many significant MAC-MAC transitions, but this trend seemed to depend on the nature of the macroscopic representations. For example, it is likely that high prior knowledge students experienced more transitions between MAC-MAC zones in the Diffusion graphic because the representations were related to one another (representing a change occurring over time). However, in the Osmosis graphic, the macroscopic representations were relatively unrelated to one another, and therefore, high prior knowledge students transitioned less frequently between these features.

The differences in transition frequencies found between high and low prior knowledge students relate to the tasks required for students to actively link macroscopic and microscopic representations. In order to comprehend graphics, learners must construct multiple mental models (Schnotz & Bannert, 2003). Because of working memory limitations, the first step involves selecting relevant features of the macroscopic and molecular representations for processing (Mayer & Moreno, 2003); however, students with high and low prior knowledge do not extract the same information. Students with low prior knowledge are less aware of the subtleties of representations and the conventions for interpreting them (Winn, 1991). Therefore, these students tend to select the most salient features of the representations for further processing, whereas students with high prior knowledge select aspects that support conceptual understanding.

The next task involves organizing the selected information into organized coherent models (Mayer, 1999). Internal connections will be made among the macroscopic features to yield a macroscopic mental model; likewise, the selected molecular features will be organized into a molecular mental model. Initially, both groups of students process the
graphics at the perceptual level and create macroscopic and molecular mental models of surface features. However, because high prior knowledge students focused on conceptually relevant features as well, they are able to go beyond perceptual models and create more abstract mental models based on underlying themes. Since students with low prior knowledge focused on superficial features of the representations, their mental models remain at the perceptual level (Schnotz, 2002; Schnotz & Bannert, 2003). This less effective mental model is usually adequate for macroscopic interpretations, since many of these representations depict observable phenomena; however perceptual mental models are not sufficient for molecular interpretations. Therefore, in this study, students with low prior knowledge transitioned more between the MAC-MAC representations, focusing on the features they had an adequate mental model for; high prior knowledge students, having more effective mental models, transitioned more between the MOL-MOL representations.

The final step requires learners to integrate their macroscopic and molecular mental representations into a single mental model. During this process, learners map the knowledge from one representation on to that of another, making one-to-one connections. For students with low prior knowledge, this coordination is difficult. These students expend many resources interpreting the macroscopic and molecular representations separately; they are left with few resources to link the representations (Seufert, 2003). Even when low prior knowledge students attempt to make linkages between the representations, because they have relied on surface features, this process is complicated. Since the important linkages between macroscopic and molecular representations primarily exist at the conceptual level, the surface features do not provide the glue necessary to link these two types of representations together. The surface features low prior knowledge students use may be adequate for linking
representations at the same level (ex. MAC-MAC features), but do not enable them to elaborate on their understanding of the scientific concepts underlying the linkages between the macroscopic and molecular representations (Kozma, 2000). Because these students are having more difficulty understanding the scientific phenomena, they typically require more MAC-MOL transitions. On the other hand, high prior knowledge students make fewer MAC-MOL transitions because the connections they make across the representations are facilitated by the underlying content.

Conclusions

The ability to coordinate multiple representations is fundamental when learning about scientific phenomena (Cheng, 1999). Numerous studies have indicated that experts and novices differ in their ability to coordinate the features of multiple representations. Although most of these studies have assessed knowledge gains, the findings of this study suggest that the difference between high and low prior knowledge learners also reveals itself in how they distribute visual attention as they are viewing the representations. Even in an AP biology class, where we assume homogeneity, students with high and low prior knowledge transitioned between MOL-MOL, MAC-MOL, and MAC-MAC representations differently. The results imply low prior knowledge learners need more guidance as they view and interpret graphics with macroscopic and molecular representations. Scaffolding though graphics or by teachers is needed so that the surface features of representations more explicitly correspond to the underlying themes.
References


Learning with multiple representations. Amsterdam: Pergamon.


EXECUTIVE SUMMARY

The purpose of this study was to examine how differentially prepared learners, specifically high school students with different amounts of domain knowledge, viewed and interpreted visual representations of cellular transport processes. Odom and Barrow’s Diffusion and Osmosis Diagnostic Test (1995) was utilized to measure prior knowledge about cell transport concepts. Eye tracking was employed to reveal how students distributed their visual attention as they perceived and interpreted graphics; in addition, interview and questionnaire responses provided more comprehensive information. The findings, presented in two manuscripts, offer a more complete understanding of how students with different amounts of domain knowledge view and interpret graphics and have the potential to inform instructional design and practice.

The first manuscript investigated the relationship between prior knowledge and students’ ability to perceive salient features and interpret graphic representations of cellular transport. Differences in how high and low prior knowledge students attended to and interpreted several features of the graphics emerged from this study. As supported by multiple data sources, low prior knowledge students focused their attention on the surface features of the graphics (ex. differences in particle color). However, these students lacked the background knowledge to interpret the deeper meaning of these features. When important features were not emphasized, students with low prior knowledge overlooked these features and their importance in understanding the graphic. On the other hand, high prior knowledge students were more likely to attend to the thematically relevant content in the graphics (regardless of its superficial saliency) and construct deeper understandings.
The second manuscript examined the influence of prior knowledge on how students transitioned among the macroscopic and molecular representations of cellular transport graphics. Eye movement measures revealed that low prior knowledge students were more likely to make macroscopic-macroscopic transitions. These students, with little domain knowledge, relied heavily on surface features to make sense of graphics. On the other hand, high prior knowledge students made more molecular-molecular transitions, suggesting that these students distributed their attention on and interpreted the conceptually relevant features. Finally, low prior knowledge students transitioned more frequently between the macroscopic and molecular representations, indicating that they were having more difficulty coordinating the different representational levels.

In addition to the data reported on in these two manuscripts, summative assessment data was collected. This assessment included items from a teacher-designed posttest as well as items focused on interpreting and creating visual representations. The items in the summative assessment do not directly relate to the data reported on in the two manuscripts and were not intended to be a test of knowledge gains resulting from the treatment. Therefore, the results of the summative assessment are not reported in this dissertation.
The Influence of Prior Knowledge on High School Students’ Interpretations of Visual Representations of Cellular Transport Processes

A Prospectus: June 29, 2005
Chapter 1: Introduction

During the past few decades, research in science education has indicated that students of all ages have difficulty understanding basic biological processes (Arnaudin & Mintzes, 1985; Johnstone & Mahmoud, 1980a; Lawson & Thompson, 1988). Specifically, middle school, high school, and college students have many misconceptions about diffusion and osmosis (Odom & Barrow, 1995; Westbrook & Marek, 1991; Zuckerman, 1993). Diffusion and osmosis are fundamental concepts in biology curricula and are keys to understanding the exchange of substances between cells and the environment, and water transport and balance in living organisms. Recent research has focused on using more effective teaching strategies, such as the learning cycle to improve understanding of these topics (Marek, Cowan, & Cavallo, 1994; Odom & Kelly, 2001); nevertheless, misconceptions seem to persist even after repeated exposure to these concepts. Since meaningful understanding requires visualization at a macroscopic, microscopic, and molecular level (Friedler, Amir, & Tamir, 1987; Sanger, Brecheisen, & Hynek, 2001), a more appropriate area of research may involve developing effective visual representations. However, developing effective instructional representations requires an understanding of how these materials are interpreted by differentially prepared learners. Therefore, the purpose of this study is to examine how prior knowledge related to cell membrane structures and processes influences how high school students view and interpret visual representations related to that topic.

Research on instructional representations has been an area of particular interest in science education. The science classroom is saturated with representations of scientific concepts and it is through these representations that knowledge is communicated from
teacher to students (van Someren et al., 1998). Since students are commonly exposed to visual displays in textbooks, teacher presentations, and computer-based multimedia materials, the ability of students to interpret and understand these representations has become increasingly important in education (Ferk et al., 2003). In general, visual representations function to attract attention and maintain motivation. They provide an additional way of representing information and foster the obtainment of knowledge that students may not get from text alone (Mayer et al., 1996). More specifically, graphics enhance information retention of associated text (Peeck, 1993), improve problem-solving, and facilitate the integration of new knowledge with prior knowledge (Roth, Bowen, & McGinn, 1999).

Visual representations are especially critical in the communication of science concepts (Mathewson, 1999). In science, graphics are used to display data, organize complex information, and promote a shared understanding of scientific phenomena (Kozma, 2003). These graphics are often used to present multiple relationships and processes that are difficult to describe. In addition, these representations illustrate phenomena that cannot be observed or experienced directly (Buckley, 2000). Since many students rely on their senses to learn, teaching the invisible and abstract concepts in science would be difficult without visuals. For this reason, visual representations aid in making abstract concepts more concrete and have the potential for improving conceptual learning (Cheng, 1999).

Although the importance of visual representations in science education has been established, more research is necessary on how to best facilitate learning with graphics. Teachers and instructional designers believe that graphics have a great deal of potential as meaning-making resources, yet in practice, visual representations do not always live up to this potential (Roth, Bowen, McGinn, 1999). To understand the role of visual
representations in science education, we must consider not only the way they are designed, but also the way they are received by different learners (Pozzer-Ardenghi & Roth, 2005). Students may have more difficulty understanding graphics than initially assumed (Wu, Krajcik, & Soloway, 2001). Even though a particular graphic may be designed to be cognitively useful, it may turn out to be functionally useless unless the learner perceives the information in the intended manner. Examining how differences in learner characteristics, such as prior knowledge, influence how learners perceive and interpret visual representations is an important first step in designing more effective instructional materials.

Prior knowledge is an important determinant of learning (Johnson & Lawson, 1998) and has been studied extensively in science education. From misconception research, there is widespread agreement that learners construct concepts from prior knowledge (Novak, 1990). However, prior knowledge not only influences subsequent conceptual learning, but also influences perception and attention. Therefore, variations in how learners interpret visual representations may be related to their existing knowledge. Learners use prior knowledge to select relevant information from graphics, add information from their prior knowledge, and ultimately, develop a mental model (Braune & Foshay, 1983).

A long tradition of research comparing experts and novices has suggested that representations do not communicate understanding to all learners equally (Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Rees, 1982). Although many of these studies focused predominately on text representations and problem-solving, their findings are applicable to visual representations as well. Students with little prior knowledge focus on surface features of visuals to build an understanding of the concepts represented (Seufert, 2003). In some cases, the most salient features of a display may not be the most relevant or important for
interpreting the representation. Because novices cannot distinguish between relevant and irrelevant information, visualizations can easily confuse these learners (Hegarty, Carpenter, & Just, 1991; Linn, 2003). Reliance on surface features may constrain the understanding of novices in other ways as well. Unlike experts, when working with multiple representations, novices are unable to see that representations with different surface features present the same underlying concept. In addition, novices are less able to transform representations, or provide an equivalent representation for a given concept (Kozma, 2003; Kozma and Russell, 1997). Visual representations can be powerful tools in science, but unfortunately, novice learners must surmount more obstacles in order for these graphics to facilitate their understanding of concepts (Perkins and Unger, 1994).

On the other hand, experts have more domain knowledge and are able to understand the important core principles represented by a graphic (Chi, Feltovich, & Glaser, 1981). In other words, they concentrate more on the information which is relevant for constructing an effective mental model (Schnotz, Picard, & Hron, 1993). The attention given to relevant information seen by experts occurs because they possess a large number of schemas specific to the domain. Even when they are exposed to novel information, experts are able to use relevant prior knowledge as a starting point for interpretation (Larkin et al., 1980).

Although expert and novice differences are clear in the literature, the influence of prior knowledge on students’ interpretations of visual representations is still in its infancy. While most of the research addresses expert and novice differences, in reality, the situation is not that simple. Students cannot merely be categorized as experts or novices; instead, they represent a continuum of prior knowledge. Because it is unclear whether more or less proficient novices differ in the same manner as experts and novices, more research is
necessary to fully explore the expert-novice continuum and discover how differentially prepared students interpret graphics. Therefore, using a mixed methods approach, the following research questions will be addressed in this study.

1. What features do students with different levels of prior knowledge use to interpret graphics?

2. How does the amount of prior knowledge influence the level of processing difficulty experienced by students?

3. How do students with differing levels of prior knowledge transition between features of the graphic?

4. How does prior knowledge influence how students interpret visual representations of passive and active transport on a macroscopic level? On a molecular level?

5. How does students’ ability to interpret graphics impact their performance on a summative assessment measuring comprehension and the ability to apply concepts learned in other contexts?

This study can offer insight into the design of visual representations. Visual representations are an important means of communicating science concepts to students, but research on how the representations are interpreted by learners is necessary. The questions asked in this study can offer a more complete understanding of how learners with differing levels of prior knowledge view and interpret graphics. The findings could be used to design visual representations to meet the needs of differentially prepared students.
This literature review provides an overview of how visual representations can be used to foster constructivist learning of science content. In the first section, an explanation of student difficulties regarding osmosis and diffusion provides a rationale for the use of visual representations in instructional materials. The second section explores how instructional presentations with visual representations are perceived from a constructivist approach. The next section examines how a learner’s prior knowledge influences the interpretation of visual representations. The fourth section addresses a major impediment to constructivist learning—the limited capacity of working memory. Finally, the last section examines how instructional design can facilitate constructivist learning from visual representations.

Diffusion and osmosis

Diffusion and osmosis are universal topics in biology curricula. These basic biological concepts are fundamental for understanding many important life processes. Unfortunately, many studies have suggested that students have difficulty understanding diffusion and osmosis correctly (Friedler, Amir, & Tamir, 1987; Johnstone & Mahmoud, 1980a; Marek, Cowan, & Cavallo, 1994; Westbrook & Marek, 1991; Zuckerman, 1994). Marek (1986) administered concept evaluation statements to tenth grade biology students to measure their understanding of diffusion and found that 37.5 percent demonstrated a sound to partial understanding of diffusion. In other words, fewer than half of the students participating in the study exhibited any degree of understanding of diffusion; the rest of the students revealed specific misconceptions or offered no response at all. In another study, Zuckerman (1995) presented high school students with an osmosis problem. Many students
were able to generate a correct answer to the problem using procedural knowledge; however, they used inappropriate or inaccurate conceptual knowledge to rationalize their responses.

Many studies have identified common misconceptions students have regarding diffusion and osmosis (Odom & Barrow, 1995; Zuckerman, 1993). Misconceptions have been described as mistakes, errors, misunderstandings, preconceptions, alternative frameworks, and naïve theories; they refer to students’ ideas that are different from those generally accepted by scientists (Odom & Barrow, 1995). Regarding diffusion and osmosis, many misconceptions exist related to basic concepts such as the particulate and random nature of matter. Many students have anthropomorphic views of matter, believing that molecules “want” to spread out and move to an area with more room (Friedler, Amir, & Tamir, 1985). These students do not understand that particles in areas of greater concentration are more likely to bounce toward other areas as a result of random interactions. In addition, some students think that molecules stop moving after equilibrium has been reached—an idea that demonstrates a lack of understanding of kinetic theory (McKnight & Hackling, 1994).

Other concepts difficult for students to understand involve solutions and dissolving. Many students will inappropriately integrate gravity concepts when presented a dissolving scenario (Odom & Settlage, 1994). For example, when asked what will happen when a small amount of sugar is added to water and allowed to sit for a very long period of time, these students will respond that the sugar will sink because it is heavier than water. In addition, they do not appear to link solvent and solute molecules, and instead hold the misconception that dissolving involves dropping solute particles into spaces in the solvent (Johnstone & Mahmoud, 1980b). Some studies have also found that students do not understand the
relationship between concentration and the amount of dissolved particles (Odom & Barrow, 1995). Finally, many students have problems with terminology, such as hypertonic, hypotonic, and isotonic. Many have incorrectly memorized the terms or have little understanding of their meaning, preventing correct application of the terms.

The misconceptions students hold may be persuasive and resistant to change, despite repeated classroom instruction. Therefore, these alternative conceptions are evident in learners of all educational levels. Westbrook and Marek (1991) conducted a cross-age study on student understanding of diffusion and found that college biology students expressed as many misconceptions as seventh graders. In fact, they suggested that older students may know more concepts to use errantly. Although students may have persistent misconceptions, research has suggested that students are not naïve about the complexity of the processes of diffusion and osmosis. High school and college students, asked to rate biology topics based on perceived difficulty reported experiencing the most trouble with this topic (Johnstone & Mahmoud, 1980a).

Researchers have begun to suggest that some of the difficulties associated with diffusion and osmosis could be reduced with visual representations that encourage students to think about these processes at a molecular level (Friedler, Amir, & Tamir, 1987; Sanger, Brecheisen, & Hynek, 2001). These representations could serve to help students grasp the abstract concepts which are necessary for complete understanding of the topic. Imagine students receiving the following scientific explanation describing osmosis without a corresponding graphic:

A U-shaped vessel has a selectively permeable membrane separating two sugar solutions of different concentrations. Pores in this synthetic membrane
are too small for sugar molecules to pass but large enough for water molecules to cross the membrane. The solution on the left side of the membrane has a lower solute concentration. It is called a hypotonic solution. The solution on the right side of the membrane has a higher solute concentration and is called a hypertonic solution. In effect the hypertonic solution has a lower water concentration; therefore, water will diffuse across the membrane from the hypotonic solution to the hypertonic solution. This diffusion of water across a selectively permeable membrane is a special case of passive transport called osmosis (Campbell & Reece, 2002).

This explanation, in words alone, would be difficult for most students to understand. However, adding a simple visual representation of the process, such as Figure 1, could significantly improve learning. In this scenario, a concrete representation could be used to help students understand what is occurring at the molecular level.

Figure 1. An example of a visual representation of osmosis that could facilitate learning from the verbal explanation. (Biology, Campbell & Reece, ©2002. Reprinted by permission of Pearson Education, Inc.)
Numerous studies have supported the use of graphics to facilitate understanding of the particulate nature of matter. Although the studies are related to topics in chemistry, they nonetheless provide support for the use of graphics with both diffusion and osmosis, since these topics cross the disciplinary boundaries of biology and chemistry (Westbrook & Marek, 1991). Research in this area has indicated that instruction involving visual representations can facilitate the development of students’ abilities to think about chemical processes at the molecular level. Gabel and Bunce (1991) were able to increase understanding at the macroscopic and molecular levels when graphics emphasized the particulate nature of matter. Likewise, research has indicated that viewing an animation of concepts involving the particulate nature of matter enhanced students’ understanding of those concepts (Williamson & Abraham, 1995). Finally, findings by Sanger (2000) suggest that when students receive chemistry instruction including particulate drawings, they are better able to answer questions about the particulate nature of matter.

Theoretical framework

Although there are many flavors and interpretations, the constructivist perspective affirms the following principle—knowledge is actively constructed by learners on the foundation of the learner’s existing knowledge (Taber, 2001). Students are not cognitively passive as they approach learning. To understand a topic fully, learners must actively link the ideas that make up a concept; in addition, they must link it with other concepts they know. When these critical linkages are made, learners tend to develop a fuller conceptual understanding of the topic (Marek, Cowan, & Cavallo, 1994; Novak & Gowin, 1984). Therefore, according to this framework, learners cannot be regarded as “blank slates;” they possess prior knowledge and this prior knowledge affects subsequent learning.
The importance of prior knowledge has been addressed in the literature mainly in terms of Ausubel’s assimilation theory of meaningful learning (Gowin, 1981; Novak, 1977; Wallace & Mintzes, 1990). According to Ausubel, education is intended to produce meaningful learning, where new information is understood and can be applied. For meaningful learning to occur, a learner must make sense out of the information presented and have relevant conceptual knowledge to anchor new ideas (Ausubel, 1968). It is a learner’s framework of relevant concepts that allow him or her to make sense out of new ideas; when these prior concepts are lacking or inappropriate, the learner has difficulty acquiring new information in the intended manner (Johnson & Lawson, 1998). As a result, rote learning may occur, which involves retention with little or no comprehension.

The constructivist framework provides a rationale for the development of techniques that provide students opportunities to construct knowledge, instead of merely dispensing it. These techniques should allow for insight into the mental models held by students (von Glasersfeld, 1995). Since constructivist learning depends on a learner’s cognitive activity rather than a learner’s behavioral activity, not all constructivist techniques involve discovery or hands-on activities (Robins & Mayer, 1993). Constructivist learning occurs when learners actively construct their own knowledge by trying to make sense out of the material presented to them. Therefore, well-designed direct instruction with visual representations can support constructivist learning provided that it promotes active cognitive processing by learners.

In order for this active processing to occur with instructional materials, Mayer and his colleagues (1996) suggest that the graphics should be explanatory in function. The representations should help clarify difficult-to-understand material, such as cause-and-effect systems. Specifically, Mayer has developed the cognitive theory of multimedia learning,
which requires learners engage in five active cognitive processes while viewing and interpreting explanatory graphics (Mayer & Anderson, 1991; Mayer & Moreno, 2003). These cognitive processes, which allow learners to construct a mental representation of presented material, involve selecting relevant words and images, organizing the relevant words and images to build verbal and visual mental models, and integrating them with one another and with relevant prior knowledge. Figure 2 illustrates the cognitive processes that take place while interpreting visual representations (Mayer, 2003, p. 129).

**Figure 2.** A framework for the cognitive theory of multimedia learning proposed by Mayer.

When both visual and verbal information are presented to the learner in instructional materials, they are briefly represented in sensory memories. Although the physical representation presented to a learner is virtually unlimited in capacity, the human information processing system is not (Mayer & Moreno, 2003). Therefore, only some of these representations will be selected for processing in working memory. Relevant words will be
selected for further processing in verbal working memory; likewise, relevant images will be
selected for further processing in visual working memory.

The selected images and words will then need to be organized into coherent models (Kintsch, 1988). Internal connections will be made among the selected images to yield a visual mental model. These images are organized into cause-and-effect chains, where former events are linked to latter events to facilitate organization into a coherent cognitive structure (Mayer, 1999). A similar process will occur with selected words to create a verbal mental model. The final step involves building external connections between the resulting visual and verbal mental models. The one-to-one connection between corresponding pictorial and verbal elements also requires the integration of relevant prior knowledge. The final result is an integrated representation of the presented material that will be stored in long-term memory for retention.

A central assumption of Mayer’s model is that working memory has dual channels, a visual channel and a verbal channel, that initially process visual and verbal information independently (Kirschner, 2002). This idea is a central feature of Paivio’s dual-coding theory and Baddeley’s theory of working memory, however many researchers do not categorize the subsystems in exactly the same way (Mayer & Moreno, 2003). Some researchers argue that both written text and narration are processed in the verbal channel; others believe that textual information is initially processed in the visual channel along with images, and ultimately those words may be translated to sounds in verbal working memory.

Prior knowledge

A learner’s prior knowledge is one of the strongest factors influencing the interpretation of representations. In Mayer’s model, relevant prior knowledge facilitates the
referential connections made between the visual and verbal mental models. However, prior knowledge also influences what visual and verbal representations will be selected for processing in working memory and how those representations will be organized into coherent visual and verbal mental models. The assertion that prior knowledge influences the cognitive processes used to interpret graphics is supported by research findings related to differences between expert and novice learners.

Novice learners are assumed to have less prior knowledge to use as a foundation for building mental representations of instructional materials. What knowledge they do have is fragmented, and pieces of information are only weakly connected (diSessa, 2004). Because they lack coherent and integrated existing knowledge, novice understanding of instructional representations tends to be constrained to surface features. When they view instructional materials, since they have insufficient or inaccurate existing knowledge about the underlying concepts represented, their mental models do not go beyond the perceptual level of processing (Chi, Feltovich, & Glaser, 1981; Schnotz, 2002). For example, in a study investigating expert and novice differences in interpreting a novel mechanics situation with weights and pulleys, Larkin (1983) found that novices search for superficial physical features, like the presence of a rope, to interpret the representation. Novices focused on functional relations (i.e. what direction the weights were being pulled), whereas experts sought out geometrical relations, such as the presence of a pivot point, to help simplify the problem.

Experts are able to go beyond superficial features because they have an abundance of relevant prior knowledge. This prior knowledge has been stored in long-term memory in schemas so that it is organized and easily accessible when needed (Chi, Glaser, & Rees,
Although a schema can hold a large amount of information, it is processed as a single unit in working memory. Therefore, when relevant prior knowledge is integrated into working memory to facilitate connections between visual and verbal mental models, it is less likely to overburden working memory (Kirschner, 2002). Because experts have well developed schemas, they attend to different information than novices (Chi, Feltovich, & Glaser, 1981). Experts link their initial visual and verbal representations to underlying principles of the content, and develop a more comprehensive mental model (Snyder, 2000).

**Limited capacity of working memory**

Meaningful learning requires that the learner engage in substantial cognitive processing, such as building referential connections between visual and verbal representations. The learner must be able to hold a visual representation and a corresponding verbal representation in working memory at the same time. Therefore, Mayer implicates working memory load, also known as cognitive load, as a major impediment to constructivist learning (Mayer et al., 1999). The limited capacity of working memory is also a central feature of cognitive load theory (Chandler & Sweller, 1992; Sweller, van Merrienboer, & Paas, 1998).

Cognitive load theory assumes that instructional presentations can impose different types of cognitive load and what type of load imposed is influenced by prior knowledge. Working memory may be affected by the inherent nature of the material and the manner in which it is presented (Kirschner, 2002). When the intention of instruction is learner understanding, it is assumed that the subject material will have a high intrinsic load. Intrinsic load is imposed by characteristics inherent in the subject matter, such as element interactivity. Elements that cannot be isolated and must be learned simultaneously in
working memory will result in high intrinsic load. If the material is low in element interactivity, the individual elements can be learned easily without imposing a heavy load on working memory. The amount of preexisting knowledge a learner has will vary the level of intrinsic load (Sweller, van Merrienboer, & Paas, 1998). With expertise, interacting elements that would otherwise overwhelm working memory can be incorporated into a schema that acts as a single element in working memory.

Any available working memory resources remaining after dealing with intrinsic cognitive load can be allocated to deal with extraneous and germane cognitive load. Though not possible with intrinsic load, both extraneous and germane cognitive load can be altered by instructional design. Germane cognitive load is imposed by information and activities that contribute to the process of schema construction and automation. Extraneous load is the effort required to process poor instructional designs (Kirschner, 2002). Any cognitive effort not directly related to constructing new schemas consumes working memory resources and decreases the capacity for learning (Kalyuga, Chandler, & Sweller, 1999). Therefore, well-designed visual representations should seek to decrease extraneous load while increasing germane load (Paas & van Merrienboer, 1993).

Understanding the relationship among the three types of cognitive load is especially important. When the material imposes a low intrinsic load due to the expertise of the learner or the ability of the material to be processed in smaller chunks, the quality of instructional design is less likely to have an impact because there is enough memory space remaining to compensate for poor design (Sweller, van Merrienboer, & Paas, 1998). However, the goal of instruction with visual representations should not be to minimize the level of total cognitive load. In fact, research has shown that performance can degrade when cognitive load is
excessively low (Paas, Renkl, & Sweller, 2004). Graphics that appear simple in content and design can easily be under-evaluated by the learner (Weidenmann, 1989). In this scenario, where intrinsic load is low and extraneous load is not an issue, an appropriate goal would be to encourage germane cognitive load.

On the other hand, excessively high loads can also impede learning. Cognitive load theory is primarily concerned with controlling the high load associated with complex information and tasks to facilitate learning (Paas, Renkl, & Sweller, 2004). In these situations, it is important to consider the source of the load. When the intrinsic load inherent in the nature of the subject material is high, schema formation will require more effort. Therefore, it will likely be necessary to reduce extraneous cognitive load in order to reduce the total cognitive load to more manageable levels. When extraneous load is reduced, more resources are free for germane load. As a consequence of acquiring and automating schema, intrinsic load is in turn reduced.

Prior knowledge has a role in categorizing information and tasks as imposing intrinsic, extraneous, or germane load. As previously suggested, a learner’s level of expertise can determine the ease with which interacting elements can be processed simultaneously in working memory without cognitive overload. In general, the less prior knowledge a learner has, the more prone he or she is to cognitive overload. However, experts are not immune to the effects of cognitive load. For example, cognitive effort that is necessary for schema construction for a novice learner may be extraneous for an expert. Since the instructional material can be perceived and interpreted differently by novices and experts, more research is necessary to design representations that will facilitate understanding for all types of learners.

*Instructional design*
The goal of instructional design is to create instructional materials in which the learner interacts meaningfully with the content. Appropriate instructional designs can help learners construct mental representations of the content, specifically by fostering the learner’s processes of selecting, organizing and integrating visual and verbal information. In addition, they should be sensitive to the issue of cognitive load and the influence of prior knowledge. Designs that help learners identify relevant information, understand how the information fits together, and see how the information relates to existing knowledge are more likely to lead to meaningful learning. These cognitive processes can be promoted through cueing, explicitly linking visual representations, and integrating visual and verbal information.

**Cueing.**

When students encounter an instructional presentation, their first cognitive activity is to select relevant words and images to be processed further in working memory. Those students with well-developed schemas are able to select the visual and verbal information most closely related to the underlying themes of the presentation (Snyder, 2000). However, students with little prior knowledge often select superficial features to interpret the material. To assist novices in selecting the appropriate information for processing, critical information should be made salient through the use of cueing techniques.

One of the most widely used techniques for attracting student attention and directing their cognitive resources to the most relevant material is the use of color. It is impossible to overestimate the role color plays in attracting attention and helping learners extract meaning from graphics (Reid and Wicks, 1988). Color can be used to highlight features in graphics, assisting students in making discriminations and detecting relationships. Using color can reduce cognitive load by reducing the need for visual search, therefore directing more
cognitive resources to the relevant material. Another technique for attracting student attention is complexity, or the amount of detail. The level of complexity must hold learner attention so that they do more than superficially view the representation; however, the level of complexity must not exceed the learner’s cognitive resources.

Mayer (1993) has suggested that the following strategies can be used to encourage students to focus on the appropriate information: headings, italics, underlining, boldface, arrows, labels, and captions. His research has also suggested that “seductive details,” interesting but irrelevant material, should be excluded (Mayer, 2003; Mayer & Moreno, 2002). Harp and Mayer (1997) found that students who read a presentation on lightning formation with irrelevant information included, performed worse on problem-solving transfer tests compared with students who read the standard booklet. These results suggest that concise presentations can also foster the selection of relevant information.

Explicitly linking visual representations.

In the typical instructional design, learners are faced with multiple representations of information in the visual modality. Multiple graphics are commonly used in chemistry, where it is important to understand the differences between symbolic, microscopic, and macroscopic representations. Multiple representations may serve to complement one another with regard to information or processes, to constrain the interpretation of one another, or to construct new connections between one another (Tsui & Treagust, 2003). They require coherence formation; learners must create referential connections between corresponding features of different visual representations. Experts are able to coordinate features within and across multiple representations and develop an understanding of underlying concepts. They
are also better able to transform representations or provide an equivalent representation for a given graphic (Kozma 2003).

For most novice learners, coordinating the representations is difficult. Novices expend much of their cognitive resources interpreting the graphic and are left with few resources to link the representations. Typically, novice learners do not make use of multiple representations, usually relying on a familiar or simple one. If switching between representations occurs, most often the learner is having difficulty understanding the representations utilized (Seufert, 2003). Even when novices attempt to interconnect representations, they often concentrate on surface features with no awareness of the underlying relevant features. For these students, translating and transforming representations is difficult, because it requires underlying knowledge about a concept.

Some instructional tools have been designed to help students more effectively coordinate multiple representations to construct deeper understanding. For example, eChem is a computer-based visualizing tool that allows students to build molecular models and view multiple representations simultaneously (Wu, Krajcik, & Soloway, 2001). Explicitly linking representations, in this case symbolic and microscopic representations, and allowing them to be viewed simultaneously reduced cognitive load. If learners are required to hold a representation in their working memory while they search for corresponding features in another representation, resources will quickly become overloaded. However, by making information explicit, learners were more likely to create referential connections between the representations. A rotation feature also helped the learners transform between representations. Externalizing the mental rotation process helped free cognitive resources to be used in learning.
**Integrating visual and verbal information.**

Although dual-mode presentations have proven to be effective, it is important that the complementary visual and verbal information is presented in a way that best facilitates student learning. When multiple sources of information are unintelligible in isolation, learners must mentally integrate the sources before they are understood (Sweller, van Merrienboer, & Paas, 1998). Integrating the information usually involves holding small segments of verbal information in working memory while searching the graphic for the matching element. When the design of the graphic does not foster the coordination of visual and verbal material, integration can be difficult as the learner’s attention is split between the two modes of information. This process of integration imposes a heavy extraneous cognitive load for novice learners, especially when the material is high in element interactivity. Only after mental integration occurs can schema acquisition begin. Because learners are assumed to have a limited working memory and more cognitive resources are required to process split-attention materials, the resources available for learning are decreased (Kalyuga, Chandler & Sweller, 2000).

It is possible to improve the instructional design of split-attention materials and decrease extraneous load by facilitating the mental integration of disparate sources of information. One way to reduce the cognitive load involved in searching for a graphical element referenced in the verbal information is to present related material contiguously in space and time (Wu & Shah, 2004). When material is presented contiguously in space and time, learners are better able to form associations between visual and verbal material (Chandler & Sweller, 1992). For example, students performed better on transfer tests when textual information was integrated into explanatory drawings than when text and drawings
were presented sequentially or when text and drawings were presented simultaneously in
time but physically spaced apart (Mayer & Gallini, 1990). In another study, students
exposed to geographic materials with text integrated into the graphic performed better on test
items than students exposed to materials that were not physically integrated (Purnell, Solman,
& Sweller, 1991). Likewise, other researchers have found that graphics and associated
narration also should be temporally and spatially coordinated to facilitate integration (Mayer
& Anderson, 1992). For example, presenting narration before or after the graphic has been
shown to impede learning.

Another way to reduce search time is to color-code related graphical and textual
elements. Research on computer-based instructions in electrical engineering indicates that by
coloring the elements of the graphic the same color as the referential text, students were
better able to integrate the information presented in two modalities. Mental load rating scales
indicated that this alternative to split-attention designs was effective due to reductions in
cognitive load (Kalyuga, Chandler, & Sweller, 1999). In a study involving narration, as
students were listening to a narration, flashing was used to indicate where on the graphic the
narration was referring. This technique can help students coordinate visual and verbal
material requiring extensive search that they might not otherwise have the cognitive
resources to coordinate. Overall, the research literature suggests that split-format designs
should be avoided to prevent cognitive load problems. Unless the learner has adequate prior
knowledge or the content material does not impose a heavy intrinsic load, the additional
processing capacity provided with dual-mode presentations will occur only if cognitive
resources do not have to be devoted to extensive search processes associated with
coordinating graphical and textual information (Jeung, Chandler, & Sweller, 1997).
Therefore, to obtain the benefits of dual-mode presentations, split-attention designs should be avoided by physically and temporally integrating the material.

Summary

Visual representations aid students in understanding relationships and processes that cannot be observed directly. Specifically, representations may help students understand diffusion and osmosis at a molecular level. Graphics can be used facilitate the active construction of knowledge allowing learners to select relevant material, organize it into coherent mental models, and integrate it with prior knowledge. The amount and accuracy of prior knowledge a learner has will influence how the visual representation is actively processed. Students with a low level of prior knowledge experience more problems with working memory overload. Although working memory load can impede constructivist learning, it is possible to design instruction in such a way that it leads to more meaningful learning.
Chapter 3: Methodology

Research Questions

The purpose of this study is to examine how prior knowledge related to cell membrane structures and process influences how Advanced Placement Biology students view and interpret visual representations related to that topic. Specifically, the following research questions will be addressed in this study.

1. What features do students with different levels of prior knowledge use to interpret graphics?
2. How does the amount of prior knowledge influence the level of processing difficulty experienced by students?
3. How do students with differing levels of prior knowledge transition between features of the graphic?
4. How does prior knowledge influence how students interpret visual representations of passive and active transport on a macroscopic level? On a molecular level?
5. How does students’ ability to interpret graphics impact their performance on a summative assessment measuring comprehension and the ability to apply concepts learned in other contexts?

The study will utilize both quantitative and qualitative research methods, allowing for comprehensive analysis and triangulation of multiple data sources (Creswell, 2003). The study is divided into two phases involving eye tracking and classroom instruction. After assessing the prior knowledge of participants in August 2005, the eye tracking phase will begin. Over the course of one month, each participant will be eye tracked as they view a
series of representations and then interviewed about those representations. After this first phase is completed, the classroom instruction phase will likely take place in October 2005. Students will receive normal classroom instruction on cell membrane structures and processes, but will be asked to fill out questionnaires on some of the representations the teacher uses in her instructional presentations. A subset of students will be interviewed to elaborate on the questionnaire data. At the culmination of this unit, students will take a teacher-designed posttest with additional items added focusing on interpreting and creating visual representations.

Population and Setting

Setting.

The participants in this study attend a parochial school in the southeastern United States. This high school serves approximately 1000 students in grades 9-12. A majority of the students are Caucasian and come from middle to upper-middle class homes. The curriculum is geared towards college preparation, and aside from fine arts courses, offers few electives. Most classes have both college preparatory (CP) sections and honors sections. If students meet the prerequisites, they can further pursue a subject in one of 13 Advanced Placement (AP) courses. Over the past 15 years, 97 percent of students graduating have attended four-year colleges.

Participants.

The subjects of this study are students enrolled in AP Biology. Assuming that all students are able to participate, approximately 60 students will be involved in this study. At this time, there are 69 students registered to take AP Biology next school year, however on average, 10 students will drop the course within the first two weeks of school. This course is
only available to seniors, most of whom are 17 years-old. Most of these students have previously taken biology as freshmen and chemistry as sophomores. The requirements for enrollment into this class are a grade of a B or better in Honors Chemistry (or an A or better in CP Chemistry) and a grade of B or better in Honors Biology (or an A or better in CP Biology). Most of the students enrolled into this course have most recently taken either AP Chemistry or CP/Honors Physics.

Teacher.

After receiving her biology degree, Margaret (a pseudonym) has pursued a MS in Earth, Space, and Environmental Science and a 6th year “Institute for Science Instruction and Study” certificate. Margaret is in her mid-fifties and has over 30 years of experience in parochial schools. In her career, she has taught both middle school and high school science, along with various math and history courses. However, her teaching experience has been interrupted by a long period of time in which she held various administrative positions, the last one being a principal of a K-8 parochial school. She has been back in the classroom for the last four years. For the second year in a row, Margaret will be teaching Anatomy and Physiology and Advanced Placement Biology to seniors.

Rationale.

As a former teacher at this high school, I am very familiar with its faculty and student population. Obtaining administrative permission, as well as targeting an appropriate teacher and course for this study was simple due to my past experience. Since I have taught AP Biology in the past, I am familiar with the curriculum and type of student taking the course. In AP Biology, topics are covered in great depth, often stressing the molecular processes at work. In addition, the students are highly motivated and mature compared to their peers.
Another benefit of selecting this particular course is that the teacher makes use of numerous visual representations in her teaching. The mode Margaret uses for conveying these graphics is through PowerPoint™ presentations. She believes, that “for a lot of concepts in biology particularly, if they see them, it makes better sense than just walking through them with words.” Margaret feels that visual representations are especially important for high ability students, “particularly because they are talking about more concepts that are combinations of concepts.” She varies the representations used so that students do not “become complacent as to what you are showing them” (Magaret, personal communication, September 30, 2004).

Assessing Prior Knowledge

Data collection.

Prior knowledge will be assessed at the beginning of the fall semester 2005 using a modified version of Odom and Barrow’s (1995) Diffusion and Osmosis Diagnostic Test, or DODT (Appendix A: Odom & Barrow’s 1995 DODT). This 24-item, two-tier, multiple-choice instrument was originally developed from research concerning alternate conceptions and other errors commonly made by students. The first tier consists of a content question with two to four choices; the second tier presents four possible reasons for the answer given on the first part. Three of the choices are common misconceptions related to the content area and one choice reflects understanding of the concept. The topics assessed by the DODT include the particulate and random nature of matter, concentration and tonicity, kinetic energy of matter, membranes, and the processes of diffusion and osmosis.

The content boundaries of the test were defined by creating a list of propositional knowledge statements required for understanding diffusion and osmosis at a level appropriate for freshman college students. The 22 propositional knowledge statements were derived
from two college-level biology textbooks and one college-level biology laboratory manual. Content validity of the instrument was established through expert judgment from a panel of two science education professors and one biology professor, by matching each test item with the propositional knowledge statements. The split-half reliability, determined from even versus odd questions, is 0.74 using the Spearman-Brown formula. The test has a mean difficulty index of 0.53, providing a wide range (from 0.23 to 0.95) of items in terms of difficulty. The discrimination indices ranged from 0.21 to 0.65, with a mean of 0.43.

Since the DODT does not cover all membrane transport processes, items were added to cover membrane permeability, active transport, and endo/exocytosis. Several items were created and piloted with 82 students in freshman biology at a high school in a different county (Appendix B: Piloted First-Tier Items and Free Response Questions). Three first-tier items were created, each with two choices. After selecting an answer, students were asked to give a written description of why they selected that particular answer. These descriptions were used to ascertain common student misconceptions and to develop appropriate distracters for the second-tier items. From their responses, 3 new question pairs were created and added to the original DODT. This procedure of using free response questions to detect common misconceptions to be used as distracters was similar to the procedure used by Odom and Barrow (1995) when developing the DODT.

The 30-item, modified DODT was piloted in May 2005 with other students at the same school where the research will occur (Appendix C: Piloted DODT). The students, sophomores in Honors Chemistry, were selected since they will not be taking AP Biology in the fall. However, they are following a similar course sequence as the typical AP Biology student and are likely to take the class when they are seniors. Eight students volunteered to
take the modified DODT. All tests were completed within 25 to 35 minutes. The students were divided into smaller groups, and after completing the test, they participated in a group discussion to elicit their comments on the test.

The following changes were made as a result of the feedback given by the students. First, phrases were added to two distracters, since many students perceived these distracters to be too simple or short in relation to other answer choices. Multiple-choice questions should be designed so that answer choices appear homogeneous (Simpson & Anderson, 1981). In question 3B, the answer choice “the molecules want to spread out,” was changed to “the molecules want to spread out into other regions.” Similarly, in question 5B, the answer choice “there will be more time for settling,” was changed to “there will more time for the sugar to settle to the bottom.” Second, the wording of two questions was altered to give students a clearer indication of time frame. In question 5A, the phrase “a very long period of time” was changed to “one week.” In question 11A, the word “immediately” was added before the phrase, “placed the dead cell in a 25% saltwater solution.” These time frame modifications are similar to ones made by Christianson and Fisher (1999) before they used the DODT.

Another suggestion from several students was to indicate that the poison mentioned in question 11A kills the cell but leaves the cell membrane intact. The question was changed to read, “Suppose you killed the plant cell in Figure 4 with poison that does not destroy the cell membrane.” Also, in question 13A, many students would have liked the chemical formula for glucose. These students indicated that information about the chemical formula would have given them clues about the size and polarity of glucose.
Finally, students had comments about the layout of the test. The students like the two-tier format, but suggested that each question-pair should be set apart from others with more space so that it is clear which questions should be answered together. Also, since the question pairs are related and students must remember part A to answer part B, they wanted both questions in the pair on the same page along with associated graphics. In addition to modifications made as a result of student suggestions an answer sheet was added for ease of scoring, along with instructions for students. The final version of the DODT that will be used to assess prior knowledge has been included in the appendix (Appendix D: DODT-Final Version).

Data analysis.

The diagnostic test will be scored to determine whether students have low or high prior knowledge about cellular membrane structures and functions. For each of the 15 pairs of questions, a student can score a maximum of three points. A correct answer on the first-tier content question will receive one point, while a correct answer on the second-tier justification question will receive two points. Correctly answering the content question may reflect memorization of the concept; however, correct responses on the justification question indicates a deeper understanding. It is important to note that students will not be given points for correct second-tier responses unless they correctly answer the first-tier question. Therefore, students will not receive points for merely guessing correctly on second-tier questions without understanding the concept.

Since the concepts assessed by this instrument are not independent of one another, students will receive a total raw score out of 45, reflecting their understanding of cell membrane structures and processes. However, in some instances, it may be more helpful to
look at students’ scores on questions related to a specific topic area. Figure 3 provides a list of topic areas addressed by the DODT along with the matching item numbers on the test. For example, if interpretation of a representation is heavily dependent on students’ knowledge of the particulate nature of matter, their combined score on questions 2, 3, and 6 can be used to measure prior knowledge. Their score in a specific topic area may be a better measure of prior knowledge as it relates to a specific representation.

<table>
<thead>
<tr>
<th>Topic Area</th>
<th>Item Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate and random nature of matter</td>
<td>2, 3, 6</td>
</tr>
<tr>
<td>Concentration and tonicity</td>
<td>4, 9</td>
</tr>
<tr>
<td>Kinetic energy of matter</td>
<td>7</td>
</tr>
<tr>
<td>Process of diffusion</td>
<td>1, 5</td>
</tr>
<tr>
<td>Process of osmosis</td>
<td>8, 10</td>
</tr>
<tr>
<td>Influence of life forces on diffusion and osmosis</td>
<td>11</td>
</tr>
<tr>
<td>Membranes</td>
<td>12, 13</td>
</tr>
<tr>
<td>Process of active transport</td>
<td>14, 15</td>
</tr>
</tbody>
</table>

*Figure 3. Topic areas with corresponding item numbers tested by the DODT.*

*Phase 1: Eye Tracking*

*Data collection.*

The first phase of the study will involve collecting data on eye movement measures to provide a view of how students with different levels of domain knowledge acquire information from graphics. After their prior knowledge is assessed, students will be eye tracked as they view visual representations of cell membrane processes on the computer. First, they will be given a visual acuity test to make sure they can see the computer screen before the eye tracking process begins. After they are seated in front of the computer screen, a headseat, used to track the parts of the eye using light reflected by the eye, will be mounted.
on their head. The mirror will be adjusted to pick up pupil-corneal reflections in the sensor, and the subject will be calibrated to the computer screen by having them look at a series of nine points. Finally, students will look at the graphics and eye movement measures will be collected.

A video-based combined pupil and corneal reflection eye tracker will collect eye movement measures, such as fixation count, fixation duration, fixation sequence, and pupil diameter, as students view the graphics. Fixations occur when the fovea, the area of the retina with the highest visual acuity, is stabilized over an object of interest. Graphics are scanned within fixations, normally lasting 200-300 milliseconds each, separated by saccades (Duchowski, 2002). Saccades are the “jumps” made to reposition the fovea from the current object to a new location. Where an individual fixates and how often can influence how a graphic is interpreted. Research indicates that individuals fixate on areas that are salient, surprising, interesting, or important through experience (Goldberg & Kotval, 1999). The sequence of fixations can provide information on which features of the graphic are compared, along with how systematically the graphic is being scanned. Fixation duration and pupil diameter provide measures of processing difficulty (Antes, Chang, & Lenzen, 1985; van Gerven et al., 2004).

Six graphics with a minimal amount of text (in the form of captions and/or labels) will be selected for eye tracking. These graphics will be typical of what one would find in textbooks and textbook supplementary materials. Selected representations of cellular transport processes will be divided such that half participants will view three of the graphics, while the other half of the participants will view the remaining graphics. The division will be made so that each group will include students with equivalent levels of prior knowledge. The
participants will be ranked based on their scores on the DODT; even-numbered rank scores will form one group, while odd-numbered ranked scores will form the other group. The presentation will be system-paced, as a previous eye tracking study by our research group has shown that students may proceed through a self-paced presentation rather quickly.

Citations of the sample graphics that will be used for this phase of research have been included in the appendix (Appendix E: Citations of Sample Representations for Eye Tracking). Figures 5-7 represent the movement of molecules across a semipermeable membrane. Each of these graphics allows the students to make comparisons, either between the two sides of the membrane or the multiple visual representations combined in the graphic. Figure 5 depicts the molecular process of diffusion across a membrane over time. Students can compare the movement of solute molecules at each stage, or can compare what this process looks like for both one and two solutes. In Figure 6, a U-tube filled with hypertonic and hypotonic solutions on each side (separated by a semipermeable membrane), illustrates the diffusion of water molecules over time. Again, students can compare the initial scenario, with the representation at equilibrium. Figure 7 also depicts osmosis. This figure portrays what happens to animal cells placed into isotonic, hypertonic, and hypotonic solutions at the molecular level and microscopic level and uses complementary diagrams and photographs. Also using equivalent diagrams and photographs, Figure 8 demonstrates endocytosis in three forms: phagocytosis, pinocytosis, and receptor-mediated endocytosis.

Numerous studies have confirmed the effectiveness of combining eye-tracking data with verbal protocols (Mackworth & Morandi, 1967; Patrick, Carter, & Wiebe, in press; Von Keitz, 1988); therefore interviews will be conducted immediately after viewing the representations to provide a more interpretive data source. The students will be shown the
same graphics in the computer presentation, this time as paper-printouts and asked the following questions about each graphic:

- Describe the most obvious features of this graphic.
- Explain what you think this graphic is trying to communicate.
- What suggestions do you have to improve this graphic?
- How would you rate the level of difficulty of this graphic (extremely difficult, somewhat difficult, neither difficult nor easy, somewhat easy, extremely easy)?

The interviews will be video recorded for the purpose of capturing any hand movements or pointing referencing particular features of the visual representations in front of them. The eye tracking and interview process is expected to take 30 minutes of a student’s time.

*Data analysis.*

On each graphic, look zones will be defined around areas of interest. For example, if a graphic is illustrating the diffusion of a substance across a membrane, one look zone would be drawn to include the area to the left of the membrane and the other look zone would be drawn to include the area to the right of the membrane. Analysis will include determining the fixation count, average fixation duration, and average pupil diameter for each subject in each look zone. With this information, one-way ANOVAs will be used to ascertain if these measures differed significantly between students with higher and lower levels of prior knowledge (as determined by the DODT). Finally, on more complex graphics like Figure 3, a lag sequential analysis will be conducted to determine how many times students transition from one look zone to another. The observed transition frequency from one look zone to another will be calculated and compared to the expected transition frequency for this same
two-event sequence. This statistic can be performed for multiple look zone transitions and
the results of students with lower and higher levels of prior knowledge can be compared.

The interview responses will be used to complement the eye tracking data. For
example, students’ descriptions of salient features can be compared to fixation count
measures. Likewise, the self-reported cognitive load rating can be compared to fixation
duration and pupil diameter measures. Overall, interview data will provide a more detailed
look into how students with lower and higher levels of prior knowledge acquired information
from the graphic.

Phase 2: Classroom Study

Data collection.

In the second phase of this study, students' interpretations of visual representations
used during classroom instruction will be examined. (In the past, instruction on membrane
structure and function has taken one week.) A subset of 5-10 visual representations used by
the teacher will be selected for study. Citations of sample graphics, used by the teacher in
previous PowerPoint™ presentations, have been included in the appendix (Appendix F:
Citations of Sample Representations for Classroom Study). The graphics focus on
interpreting the molecular movement of molecules across a semipermeable membrane
compared to equivalent diagrams at the macroscopic level; comparing the effects on plant
and animal cells when they are placed in isotonic, hypertonic, and hypotonic solutions;
differentiating between diffusion, facilitated diffusion, and active transport; and understanding
the active transport of sodium and potassium.
Throughout the instructor's presentation on membrane structure and function, the students will be shown these graphics and their interpretations of the graphics prior to teacher explanation will be assessed by:

- a self-reported rating of the difficulty level of the graphic (extremely difficult, somewhat difficult, neither difficult nor easy, somewhat easy, extremely easy), previously established by Paas and van Merrienboer (1993).

- an instructional representation questionnaire. Specific questions will depend on the characteristics of the visual representations, however, some general questions might include 1) What idea is this graphic communicating? 2) What features of the graphic did you use to make your interpretation? Each questionnaire should take no more than five minutes to complete.

At the end of the classroom instruction phase, a minimum of 10 students will interviewed. The students interviewed will be volunteers, offering to be interviewed for 15 minutes outside of class time. For each student, 2-3 of the visual representations used in the classroom study phase will be selected and shown in paper-form. The student will be asked questions similar to those on the written instructional representations questionnaire. The purpose of these interviews is to provide a richer data source, since students tend to elaborate more when speaking than when writing. The interviews will be video recorded, again with the intention of capturing any hand movements or pointing referencing particular features of the visual representations in front of them. In addition, the classroom instruction phase will also be video recorded for the purpose of capturing what visual representations were used by the teacher and in what order, and to record the explanations given by the teacher about each representation.
A teacher-designed posttest will be given at the end of the unit. A typical posttest includes multiple-choice questions and one or two essay questions, taking 45-60 minutes to complete. The test is designed to measure student comprehension of the concepts presented during classroom instruction along with their ability to predict and apply their knowledge about the topic. For this unit, questions will be added that focus on interpreting and creating representations. Students will be asked to interpret representations similar to those seen in classroom instruction. In addition, a question that requires students to draw their own representations will be included.

*Data analysis.*

The responses from the questionnaires and interviews will be analyzed using the constant comparative method (Strauss & Corbin, 1998). Initially, the data will be coded to develop categories; however, the key strategy will be to constantly compare these categories. Categories that emerge will be compared from one participant to the next and from one data source to the next. Constant comparison will allow for the categories to be interrelated and refined, so that patterns in how students interpret graphics may be discovered (Hatch, 2002). Specifically, the patterns identified that pertain to how students interpret graphics at the macroscopic and molecular levels and what features of the graphic they use to facilitate interpretation will be compared to DODT scores to reveal differences between students with lower and higher levels of prior knowledge.

In addition to questionnaire and interview data, other data sources will be analyzed as well. To reveal how prior knowledge influences students’ perceptions of graphics, a one-way ANOVA will be used to determine if significant differences in the self-reported rating of difficulty level exist between students with differing levels of prior knowledge. Finally,
analysis will be conducted to determine if there is a relationship between their level of success at interpreting visual representations and consequent performance on the posttest. Scores on both the posttest overall and the items focused on interpreting and creating visual representations will be compared to students’ ability to interpret graphics during the classroom instruction phase.

Summary

The purpose of this study is to determine how prior knowledge influences how students interpret visual representations. Figure 4 summarizes the research questions that will addressed in each phase of the study, along with data collection and analysis procedures.
<table>
<thead>
<tr>
<th>Phase of Study</th>
<th>Research Questions</th>
<th>Data Collection</th>
<th>Data Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye Tracking</td>
<td>What features do students with differing levels of prior knowledge use to interpret graphics? How does the amount of prior knowledge influence the level of processing difficulty experienced by students? How do students with differing levels of prior knowledge transition between features of the graphic?</td>
<td>Eye movement measures: fixation count, fixation duration, sequence of fixations, pupil diameter Interviews-all participants</td>
<td>One-way ANOVAs to determine if significant differences in eye tracking measures exist between students with differing levels of prior knowledge Interviews coded using constant comparison method to find patterns in how students view and interpret graphics; results will be compared to eye movement data</td>
</tr>
<tr>
<td>Classroom Study</td>
<td>How does prior knowledge influence how students interpret visual representations of passive and active transport on a macroscopic level? On a molecular level? What features do students with differing levels of prior knowledge use to interpret graphics? How does prior knowledge influence students’ self-reported rating of the difficulty level of the graphic? How does their ability to interpret graphics impact their performance on a summative assessment?</td>
<td>Questionnaires and self-reported rating of difficulty level on each representation used Interviews-a subset of participants Posttest</td>
<td>Questionnaires and interviews coded using constant comparison method to find patterns in how students view and interpret graphics One-way ANOVA to determine if significant differences in self-reported rating of difficulty level exist between students with differing levels of prior knowledge. Scores on relevant posttest items and overall posttest scores compared to student’s success at interpreting graphics in classroom instruction phase</td>
</tr>
</tbody>
</table>

*Figure 4.* A summary of research questions and procedures proposed for this study.
References


Annual Meeting of the National Association for Research in Science Teaching,
Anaheim, CA.

the interaction between information structures and cognitive architecture.
*Instructional Science, 32*, 1-8.

approach to combine mental effort and performance measures. *Human Factors*,
35(4), 737-743.

Replication: Middle Grades Students' Perceptions and Interpretations. *Journal of
Science Education and Technology*.

Peeck, J. (1993). Increasing picture effects in learning from illustrated text. *Learning and
Instruction, 3*, 227-238.


89*(2), 219-241.


Reid, D. J., & Wicks, S. Y. (1988). Children's perception of colour on a school

Educational Psychology, 85*, 529-538.


Appendix A
Odom & Barrow’s (1995) DODT (24 items)

Diffusion and Osmosis Test

Directions: DO NOT WRITE ON THE ASSESSMENT. This assessment consists of 12 pairs of questions to examine your knowledge of diffusion and osmosis. Each question has two parts: a multiple-choice response followed by a multiple-choice reason. On the answer sheet provided, please circle one answer from both the response and reason sections of each question.

1A. Suppose there is a large beaker full of clear water and a drop of blue dye is added to the beaker of water. Eventually the water will turn a light blue color. The process responsible for blue dye becoming evenly distributed throughout the water is:
   a. osmosis
   b. diffusion
   c. a reaction between water and dye

1B. The reason for my answer is because:
   a. The lack of a membrane means that osmosis and diffusion can occur.
   b. There is movement of particles between regions of different concentrations
   c. The dye separates into small particles and mixes with water.
   d. The water moves from one region to another.

2A. During the process of diffusion, the particles will generally move from:
   a. high to low concentrations
   b. low to high concentrations

2B. The reason for my answer is because:
   a. There are too many particles crowded into one area; therefore, they move to an area with more room.
   b. Particles in areas of greater concentration are more likely to bounce toward other areas.
   c. The particles tend to move until the two areas are isotonic, and then the particles stop moving.
   d. There is a greater chance of the particles repelling each other.

3A. As the difference in concentration between two areas increases, the rate of diffusion:
   a. decreases
   b. increases
3B. The reason for my answer is because:
   a. There is less room for particles to move.
   b. If the concentration is high enough, the particles will spread less and the rate will be
      slowed.
   c. The molecules want to spread out.
   d. There is a greater likelihood of random motion in other regions.

4A. A glucose solution can be made more concentrated by:
   a. adding more water
   b. adding more glucose

4B. The reason for my answer is because:
   a. The more water there is, the more glucose it will take to saturate the solution.
   b. Concentration means the dissolving of something.
   c. It increases the number of dissolved particles.
   d. For a solution to be more concentrated, one must add more liquid.

5A. If a small amount of sugar is added to a container of water and allowed to set for a very
long period of time without stirring, the sugar molecules will:
   a. be more concentrated on the bottom of the container
   b. be evenly distributed throughout the container

5B. The reason for my answer is because:
   a. There is movement of particles from a high to low concentration.
   b. The sugar is heavier than water and will sink.
   c. Sugar dissolves poorly or not at all in water.
   d. There will be more time for settling.

6A. Suppose you add a drop of blue dye to a container of clear water and after several hours
the entire container turns light blue. At this time, the molecules of dye:
   a. have stopped moving
   b. continue to move around randomly

6B. The reason for my answer is because:
   a. The entire container is the same color; if they were still moving, the container would
      be different shades of blue
   b. If the dye molecules stopped, they would settle to the bottom of the container.
   c. Molecules are always moving.
   d. This is a liquid; if it were solid the molecules would stop moving.
7A. Suppose there are two large beakers with equal amounts of clear water at two different temperatures. Next, a drop of green dye is added to each beaker of water. Eventually the water turns light green (see Figure 1). Which beaker became light green first?
   a. Beaker 1
   b. Beaker 2

![Figure 1.](image)

7B. The reason for my answer is because:
   a. The lower temperature breaks down the dye.
   b. The dye molecules move faster at higher temperatures.
   c. The cold temperature speeds up molecules.
   d. It helps the molecules to expand.

8A. In Figure 2, two columns of water are separated by a membrane through which only water can pass. Side 1 contains dye and water; side 2 contains pure water. After 2 hours, the water level in side 1 will be:
   a. higher
   b. lower
   c. the same height

![Figure 2.](image)
8B. The reason from my answer is because:
   a. Water will move from the hypertonic to hypotonic solution.
   b. The concentration of water molecules is less on side 1.
   c. Water will become isotonic.
   d. Water moves from low to high concentrations.

9A. In Figure 3, side 1 is _______ to side 2.
   a. hypotonic
   b. hypertonic
   c. isotonic

![Figure 3](image_url)

9B. The reason from my answer is because:
   a. Water is hypertonic to most things.
   b. Isotonic means “the same.”
   c. Water moves from a high to a low concentration.
   d. There are fewer dissolved particles on side 1.

10A. Figure 4 is a picture of a plant cell that lives in freshwater. If this cell were placed in a beaker of 25% saltwater solution, the central vacuole would:
   a. increase in size
   b. decrease in size
   c. remain the same size
10B. The reason for my answer is because:
   a. Salt absorbs the water from the central vacuole.
   b. Water will move from the vacuole to the saltwater solution.
   c. The salt will enter the vacuole.
   d. Salt solution outside the cell cannot affect the vacuole inside the cell.

11A. Suppose you killed the plant cell in Figure 4 with poison and placed the dead cell in a 25% saltwater solution.
   a. Osmosis and diffusion would not occur.
   b. Osmosis and diffusion would continue.
   c. Only diffusion would continue.
   d. Only osmosis would continue.

11B. The reason from my answer is because:
   a. The cell would stop functioning.
   b. The cell does not have to be alive.
   c. Osmosis is not random, whereas diffusion is a random process.
   d. Osmosis and diffusion require cell energy.

12A. All cell membranes are:
   a. semipermeable
   b. permeable

12B. The reason for my answer is because:
   a. They allow some substances to pass.
   b. They allow some substances to enter, but they prevent any substance from leaving.
   c. The membrane requires nutrients to live
   d. They allow all nutrients to pass.
Appendix B
Piloted First-Tier Items and Free Response Questions

For each question that follows, circle the appropriate answer and provide an explanation for your answer.

1A. Glucose diffuses in and out of the cell through
   a. the lipid bilayer
   b. transport proteins

1B. The reason for my answer is because:

2A. Cells maintain a much higher concentration of potassium inside the cell compared to its surroundings through the process of
   a. passive transport
   b. active transport

2B. The reason for my answer is because:

3A. Proteins and very large carbohydrates enter the cell through the process of
   a. facilitated diffusion
   b. endocytosis

3B. The reason for my answer is because:
Appendix C
Piloted DODT (with 30 items)

Name: _________________________________

1A. Suppose there is a large beaker full of clear water and a drop of blue dye is added to the beaker of water. Eventually the water will turn a light blue color. The process responsible for blue dye becoming evenly distributed throughout the water is:
   a. osmosis
   b. diffusion
   c. a reaction between water and dye

1B. The reason for my answer is because:
   a. The lack of a membrane means that osmosis and diffusion can occur.
   b. There is movement of particles between regions of different concentrations
   c. The dye separates into small particles and mixes with water.
   d. The water moves from one region to another.

2A. During the process of diffusion, the particles will generally move from:
   a. high to low concentrations
   b. low to high concentrations

2B. The reason for my answer is because:
   a. There are too many particles crowded into one area; therefore, they move to an area with more room.
   b. Particles in areas of greater concentration are more likely to bounce toward other areas.
   c. The particles tend to move until the two areas are isotonic, and then the particles stop moving.
   d. There is a greater chance of the particles repelling each other.

3A. As the difference in concentration between two areas increases, the rate of diffusion:
   a. decreases
   b. increases

3B. The reason for my answer is because:
   a. There is less room for particles to move.
   b. If the concentration is high enough, the particles will spread less and the rate will be slowed.
   c. The molecules want to spread out.
   d. There is a greater likelihood of random motion in other regions.
4A. A glucose solution can be made more concentrated by:
   a. adding more water
   b. adding more glucose

4B. The reason for my answer is because:
   a. The more water there is, the more glucose it will take to saturate the solution.
   b. Concentration means the dissolving of something.
   c. It increases the number of dissolved particles.
   d. For a solution to be more concentrated, one must add more liquid.

5A. If a small amount of sugar is added to a container of water and allowed to set for a very
long period of time without stirring, the sugar molecules will:
   a. be more concentrated on the bottom of the container
   b. be evenly distributed throughout the container

5B. The reason for my answer is because:
   a. There is movement of particles from a high to low concentration.
   b. The sugar is heavier than water and will sink.
   c. Sugar dissolves poorly or not at all in water.
   d. There will be more time for settling.

6A. Suppose you add a drop of blue dye to a container of clear water and after several hours
the entire container turns light blue. At this time, the molecules of dye:
   a. have stopped moving
   b. continue to move around randomly

6B. The reason for my answer is because:
   a. The entire container is the same color; if they were still moving, the container would
      be different shades of blue
   b. If the dye molecules stopped, they would settle to the bottom of the container.
   c. Molecules are always moving.
   d. This is a liquid; if it were solid the molecules would stop moving.

7A. Suppose there are two large beakers with equal amounts of clear water at two different
temperatures. Next, a drop of green dye is added to each beaker of water. Eventually the
water turns light green (see Figure 1). Which beaker became light green first?
   a. Beaker 1
   b. Beaker 2
7B. The reason for my answer is because:
   a. The lower temperature breaks down the dye.
   b. The dye molecules move faster at higher temperatures.
   c. The cold temperature speeds up molecules.
   d. It helps the molecules to expand.

8A. In Figure 2, two columns of water are separated by a membrane through which only water can pass. Side 1 contains dye and water; side 2 contains pure water. After 2 hours, the water level in side 1 will be:
   a. higher
   b. lower
   c. the same height

8B. The reason from my answer is because:
   a. Water will move from the hypertonic to hypotonic solution.
   b. The concentration of water molecules is less on side 1.
   c. Water will become isotonic.
   d. Water moves from low to high concentrations.
9A. In Figure 3, side 1 is _______ to side 2.
   a. hypotonic
   b. hypertonic
   c. isotonic

9B. The reason from my answer is because:
   a. Water is hypertonic to most things.
   b. Isotonic means “the same.”
   c. Water moves from a high to a low concentration.
   d. There are fewer dissolved particles on side 1.

10A. Figure 4 is a picture of a plant cell that lives in freshwater. If this cell were placed in a beaker of 25% saltwater solution, the central vacuole would:
   a. increase in size
   b. decrease in size
   c. remain the same size
10B. The reason for my answer is because:
   a. Salt absorbs the water from the central vacuole.
   b. Water will move from the vacuole to the saltwater solution.
   c. The salt will enter the vacuole.
   d. Salt solution outside the cell cannot affect the vacuole inside the cell.

11A. Suppose you killed the plant cell in Figure 4 with poison and placed the dead cell in a 25% saltwater solution.
   a. Osmosis and diffusion would not occur.
   b. Osmosis and diffusion would continue.
   c. Only diffusion would continue.
   d. Only osmosis would continue.

11B. The reason from my answer is because:
   a. The cell would stop functioning.
   b. The cell does not have to be alive.
   c. Osmosis is not random, whereas diffusion is a random process.
   d. Osmosis and diffusion require cell energy.

12A. All cell membranes are:
   a. semipermeable
   b. permeable

12B. The reason for my answer is because:
   a. They allow some substances to pass.
   b. They allow some substances to enter, but they prevent any substance from leaving.
   c. The membrane requires nutrients to live
   d. They allow all nutrients to pass.
13A. Glucose diffuses in and out of the cell through
   a. the lipid bilayer
   b. transport proteins

13B. The reason for my answer is because:
   a. Glucose is a small molecule, much smaller than a water molecule.
   b. Glucose is a polar molecule and hydrophilic.
   c. Glucose does not have a charge.
   d. Glucose moves in and out of the cell without requiring energy.

14A. Cells maintain a much higher concentration of potassium inside the cell compared to its surroundings through the process of
   a. passive transport
   b. active transport

14B. The reason for my answer is because:
   a. Potassium is moving down its concentration gradient.
   b. Potassium travels through transport proteins.
   c. Energy is required to maintain the concentration gradient.
   d. The transport of potassium is sped up.
   e. Water is moving out of the cell at the same time.

15A. Proteins and very large carbohydrates enter the cell through the process of
   a. facilitated diffusion
   b. endocytosis
   c. exocytosis

15B. The reason for my answer is because:
   a. The membrane only allows certain substances to pass.
   b. These molecules are polar/charged.
   c. Transport proteins are involved.
   d. These molecules are large.
Appendix D
DODT-Final Version

Diffusion and Osmosis Test

Directions: This test contains 30-items in a paired format to examine your knowledge on diffusion and osmosis. For part A of each question, you are asked to select the most appropriate choice. For part B of each question, you are asked to give the most scientifically appropriate reason for your choice in part A. PLEASE DO NOT WRITE ON THE TEST; instead, write your answers on the answer-sheet provided.

1A. Suppose there is a large beaker full of clear water and a drop of blue dye is added to the beaker of water. Eventually the water will turn a light blue color. The process responsible for blue dye becoming evenly distributed throughout the water is:
   a. osmosis
   b. diffusion
   c. a reaction between water and dye

1B. The reason for my answer is because:
   a. The lack of a membrane means that osmosis and diffusion can occur.
   b. There is movement of particles between regions of different concentrations
   c. The dye separates into small particles and mixes with water.
   d. The water moves from one region to another.

2A. During the process of diffusion, the particles will generally move from:
   a. high to low concentrations
   b. low to high concentrations

2B. The reason for my answer is because:
   a. There are too many particles crowded into one area; therefore, they move to an area with more room.
   b. Particles in areas of greater concentration are more likely to bounce toward other areas.
   c. The particles tend to move until the two areas are isotonic, and then the particles stop moving.
   d. There is a greater chance of the particles repelling each other.
3A. As the difference in concentration between two areas increases, the rate of diffusion:
   a. decreases
   b. increases

3B. The reason for my answer is because:
   a. There is less room for particles to move.
   b. If the concentration is high enough, the particles will spread less and the rate will be slowed.
   c. The molecules want to spread out into other regions.
   d. There is a greater likelihood of random motion into other regions.

4A. A glucose solution can be made more concentrated by:
   a. adding more water
   b. adding more glucose

4B. The reason for my answer is because:
   a. The more water there is, the more glucose it will take to saturate the solution.
   b. Concentration means the dissolving of something.
   c. It increases the number of dissolved particles.
   d. For a solution to be more concentrated, one must add more liquid.

5A. If a small amount of sugar is added to a container of water and allowed to set for one week without stirring, the sugar molecules will:
   a. be more concentrated on the bottom of the container
   b. be evenly distributed throughout the container

5B. The reason for my answer is because:
   a. There is movement of particles from a high to low concentration.
   b. The sugar is heavier than water and will sink.
   c. Sugar dissolves poorly or not at all in water.
   d. There will be more time for the sugar to settle to the bottom.
6A. Suppose you add a drop of blue dye to a container of clear water and after several hours the entire container turns light blue. At this time, the molecules of dye:
   a. have stopped moving
   b. continue to move around randomly

6B. The reason for my answer is because:
   a. The entire container is the same color; if they were still moving, the container would be different shades of blue
   b. If the dye molecules stopped, they would settle to the bottom of the container.
   c. Molecules are always moving.
   d. This is a liquid; if it were solid the molecules would stop moving.

7A. Suppose there are two large beakers with equal amounts of clear water at two different temperatures. Next, a drop of green dye is added to each beaker of water. Eventually the water turns light green (see Figure 1). Which beaker became light green first?
   a. Beaker 1
   b. Beaker 2

![Figure 1.](image)

7B. The reason for my answer is because:
   a. The lower temperature breaks down the dye.
   b. The dye molecules move faster at higher temperatures.
   c. The cold temperature speeds up molecules.
   d. It helps the molecules to expand.
8A. In Figure 2, two columns of water are separated by a membrane through which only water can pass. Side 1 contains dye and water; side 2 contains pure water. After 2 hours, the water level in side 1 will be:
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![Figure 3.](image)

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   c. remain the same size

![Figure 4.](image)

10B. The reason for my answer is because:
   a. Salt absorbs the water from the central vacuole.
   b. Water will move from the vacuole to the saltwater solution.
   c. The salt will enter the vacuole.
   d. Salt solution outside the cell cannot affect the vacuole inside the cell.

11A. Suppose you killed the plant cell in Figure 4 with poison (that does not destroy the cell membrane) and immediately placed the dead cell in a 25% saltwater solution.
   a. Osmosis and diffusion would not occur.
   b. Osmosis and diffusion would continue.
   c. Only diffusion would continue.
   d. Only osmosis would continue.

11B. The reason from my answer is because:
   a. The cell would stop functioning.
   b. The cell does not have to be alive.
   c. Osmosis is not random, whereas diffusion is a random process.
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   c. The membrane requires nutrients to live
   d. They allow all nutrients to pass.

13A. Glucose (C₆H₁₂O₆) diffuses in and out of the cell through
   a. the lipid bilayer
   b. transport proteins

13B. The reason for my answer is because:
   a. Glucose is a small molecule, much smaller than a water molecule.
   b. Glucose is a polar molecule and hydrophilic.
   c. Glucose does not have a charge.
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14B. The reason for my answer is because:
   a. Potassium is moving down its concentration gradient.
   b. Potassium travels through transport proteins.
   c. Energy is required to maintain the concentration gradient.
   d. The transport of potassium is sped up.
   e. Water is moving out of the cell at the same time.
15A. Proteins and very large carbohydrates enter the cell through the process of
   a. facilitated diffusion
   b. endocytosis
   c. exocytosis

15B. The reason for my answer is because:
   a. The membrane only allows certain substances to pass.
   b. These molecules are polar/charged.
   c. Transport proteins are involved.
   d. These molecules are large.
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<th>Question Number</th>
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Appendix E
Citations of Sample Representations for Eye Tracking

Figure 5:
Campbell & Reece, 2002, p. 145

Figure 6:
Campbell & Reece, 2002, p. 146

Figure 7:
Solomon, Berg, & Martin, 2002, p. 115

Figure 8:
Campbell & Reece, 2002, p. 152


Appendix F
Citations of Sample Representations for Classroom Study

Figure 9:
Solomon, Berg, & Martin, 2002, p. 113

Figure 10:
Campbell & Reece, 2002, p. 147

Figure 11:
Campbell & Reece, 2002, p. 150

Figure 12:
Campbell & Reece, 2002, p. 149
