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THINKING BEYOND THE FRIED EGG MODEL: HOW ACCURATELY DO STUDENTS PERCEIVE CELLS IN A LIVING CONTEXT?

By

Milissa Knox

B.S. University of Maine, 2008

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Teaching

The Graduate School

The University of Maine

December 2015

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THESIS ACCEPTANCE STATEMENT

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Dr. Molly Schauffler, Assistant Research Professor 10/13/15

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THINKING BEYOND THE FRIED EGG MODEL: HOW ACCURATELY DO STUDENTS PERCEIVE CELLS IN A LIVING CONTEXT?

By Milissa Knox

Thesis Advisor: Dr. Molly Schauffler

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
Degree Master of Science in Teaching
December 2015

This exploratory study investigated three aspects of introductory undergraduate biology students' understanding about cells. The study, which took place at the University of Maine with voluntary students in Basic Biology ("BIO100") in the summer and fall of 2009, examined (1) students' pre-course perceptions of cells as they exist in a living context and (2) gains in students' perception and knowledge about cells after completing the one-semester course (BIO100). Results are based on lecture exam scores, pre-post surveys developed as a part of this thesis, and interviews with two groups of biology students. A total of 498 students participated in the study. Of that group, 25 students participated in either the pre- and post-instruction survey or an interview (summer survey (n=15) and fall interview (n=10)). Results suggest that (1) students enter BIO100 with inaccurate perceptions about how living cells vary in shape, size, and function, and that, (2) students' *factual knowledge* about cells (such as the ability to identify parts of a cell) significantly improves during BIO100 but their *contextual*

understanding (such as that cell size can range from a microscopic bacterium to a large ostrich egg) does not improve during the course. Suggestions are offered for how high school or undergraduate curriculum and assessments might be aligned not only to emphasize content knowledge, but also to help students acquire a more accurate perception of the diversity of cell structure and function in living contexts.

DEDICATION

This thesis is dedicated to my husband, Justin Knox. This work would not have been completed without your love and encouragement through this entire journey. This thesis is also dedicated to my grandparents, Ethel and Wilmot Lewis, who provided support and love during my childhood and whose good examples taught me to work hard and think creatively.

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CHAPTER 1

INTRODUCTION

A cell is the smallest unit of life. Understanding how cells function in living organisms is fundamental to understanding all of what is taught in the biology classroom. Cells are highly complex and variable in size and function. In the human body alone there are 210 known distinct cell types, each of which have specialized functions and all of which operate together in order to enable us to thrive. Cell structures and functions are taught in secondary and undergraduate education science courses to ensure students understand how their own body works. Traditional biology curriculum tends to focus on facts about cells, such as structures and functions of organelles. New standards are placing less emphasis on rote cellular knowledge and more on students' conceptual understanding of larger ideas, such as cells in the living system.

1.1 Purpose of study

This thesis investigated what undergraduate students in a basic biology course at the University of Maine understand about cells. Lecture exams, surveys, and interviews were used to gain insight into students' knowledge and perceptions of cells. Comparisons in knowledge and before and after instruction were examined to determine the impact of the introductory course, BIO100, on the students' knowledge of cells.

1.2 Research questions

1. At what cognitive level do BIO100 students understand that cells vary *in the context of the living organism*?
2. What gains in knowledge and contextual understanding of cells do students make during BIO100?

3. Is there any correlation between how well students do on the BIO100 cell exam questions and their SAT scores and BIO100 grades?

1.3 Basic biology course description

Basic biology (BIO 100) is offered each semester by The School of Ecology and Biology at The University of Maine. It is described in The University of Maine's course catalog as: "An introduction to the following fundamental topics in biology: the structure and function of cells, the molecular basis and mechanisms of genetic inheritance, concepts in evolution, mechanisms of metabolism, and ecology."

It is taught as a four-credit course with 3 hours of lecture and a mandatory two-hour laboratory each week. At the time of this study, the lecture portion of the class was conducted in lecture halls using PowerPoint as the primary teaching tool. In the laboratory, groups work from a lab manual with guidance from Teaching Assistants (TAs). The course is offered in the fall, spring, and summer semesters.

The 2009 fall and spring courses consisted of three 50-minute lecture sections that met Monday, Wednesday, and Friday. Each lecture section has a capacity of 250 students. The lab groups consist of approximately 18 students and met once a week for 2 hours. There are approximately 41 different lab sections. The laboratories were redesigned to incorporate more student-centered inquiry, instead of a step-by-step approach directed by the lab manual. In approximately 2011, BIO 100 lectures were developed for online delivery, and students can now chose the lecture format they prefer.

In the summer, BIO100 is condensed into approximately one month, beginning in June. Approximately 50 students attend five 90-minute lectures and two 2-hour labs per week. There is only one lab and one lecture section available in the summer.

One instructor taught both the summer and fall 2009 courses, which was the instructor from the previous year. In the fall of 2009 supplemental online material was available for the students. The online material included videos that were primarily composed of visual diagrams with background audio of the instructor's voice.

1.4 Road map of the thesis

The structure of the thesis and content is as follows. In Chapter 2, the background literature is described and covers the topics of learning standards and what students have difficulties with when learning about cell structures and functions. Chapter 3 gives the methods used to investigate biology students' knowledge and comprehension of cells in the living context. Chapter 4 outlines the results that were obtained. Chapter 5 provides a discussion of the results and teaching implication and the conclusion of the study.

CHAPTER 2

LITERATURE REVIEW

Although cells are fundamental building blocks of life, teaching about fundamental structures and functions of cells is challenging because most cells and cell functions occur at scales too small to witness with the naked eye. Processes carried out by living cells *in situ* (e.g., transcription and translation, photosynthesis, protein synthesis, and respiration) occur deep within living organisms and they cannot easily be manipulated and measured in a classroom as can physical phenomena such as gravity, velocity, and heat transfer.

Benchmarks and learning standards are available to guide lesson design, curriculum progression, and grade-specific desired levels of thinking and reasoning for students learning about living cells. This chapter reviews published research about learning expectations and difficulties students face when trying to meet the benchmarks for understanding about living cells.

The following questions are reviewed in this chapter:

1) What are students expected to learn about cells?
2) What difficulties do students encounter when learning about cells, and what alternate conceptions do they acquire?

2.1. What are students expected to learn about cells?

2.1.1. What standards are available to guide students' learning about cells?

The Association for the Advancement of Science (AAAS) Project 2061 Benchmarks for Science Literacy (BSL), the National Science Education Standards (NSES) by the National Research Council (NRC), and (for the State of Maine) The

Maine State Learning Results for Science and Technology, outline science concepts with which students are expected to be proficient after completion of high school (AAAS, 1993; NRC, 1996, & MDOE, 2007). Ideally, students will have attained these standards upon entering the University of Maine's basic biology course, BIO100. Since the present study was completed, the National Academy of Sciences, with the help of many science educators around the country, has drafted a new set of standards for science and engineering education: the Next Generation Science Standards (NGSS). Fourteen states have adopted these standards, and Maine Legislature is on the verge of voting to adopt the NGSS at this writing. Although Maine will likely soon adopt the NGSS, most of the undergraduates in BIO 100 at the University of Maine graduated from a Maine high school prior to 2009, when this work was undertaken. For that reason, the Maine Learning Results Science and Technology Standards are discussed here as well as the new NGSS (MDOE, 2007; NGSS, 2013).

The NGSS differs from the other science standards by connecting other discipline's learning standards (e.g., literacy and mathematical Common Core Standards). The NGSS's framework integrates technology and engineering (e.g., developing models, constructing explanations, performing scientific investigations), crosscutting concepts (e.g., systems and system models, energy and matter, structure and function, stability and change), and science core ideas (e.g., cell structure and function). Rather than focusing on isolated disciplinary-specific content, such as identifying specific types of cells or listing specific steps of cellular respiration, the standards encourage a deeper understanding of the content by applying the crosscutting concepts to technology and engineering procedures (i.e., modeling cellular processes) (NGSS, 2013; NRC, 2012).

2.1.2. What is the kindergarten through 12th grade learning progression for learning about cells?

The progression of cognitive demand for the *MLR* standards was based on Bloom's Taxonomy, a categorization of learning objectives. Bloom's taxonomy differs from Piaget's cognitive development theory, in that it is not based on developmental stages, but progressive learning goals. The taxonomy consists of six types of objectives, arranged from simple to complex; each previous objective is a prerequisite for the next: knowledge, comprehension, application, analysis, synthesis, and evaluation (Bloom, 1956) (Table 2.1.).

Table 2.1. Classification of learning objectives in Bloom's taxonomy from lowest to highest (Bloom, 1956)

Cognitive domain	Description
Knowledge	Recalling facts such as terminology, classifications, methodology, theories, and structures
Comprehension	Understanding facts and ideas by organizing, comparing, describing, and extrapolating main ideas
Application	Using previously learned knowledge to solve a problem in a new situation
Analysis	Examine information to make inferences
Synthesis	Compile information to create solutions
Evaluation	Present and defend opinions by making judgments about information

The general grammatical format of each *MLR* specified the content students are expected to learn and to what cognitive depth; the verb used (e.g., demonstrate, discuss, or examine) reflects the levels of Bloom's taxonomy (Anderson, 2005). From pre-kindergarten to diploma, students were expected to advance from learning content knowledge, to comprehension, to application of the content standards (Table 2.2.) (MDOE, 2007).

Table 2.2. Cognitive demand for content standards about cells (Maine Learning Results) (MDOE, 2007).

Grade band	Cell content standards	At what level of Bloom's taxonomy is the cognitive demand?
Pre-K-2	Demonstrate that living things are made of different parts.	Comprehension
	Demonstrate an understanding that plants and animals need food, water, and gases to survive.	Knowledge
	Investigate magnifying devices and how they allow one to see more detail.	Knowledge
3-4	Demonstrate an understanding that a cell is the basic unit of living organisms.	Knowledge
	Describe how single-celled organisms exist.	Application
	Use microscopes to see cells in a variety of organisms.	Application
	Describe the functions of the major human organ systems	Comprehension
5-8	Compare and contrast human organ systems with those of other species.	Application
	Prepare and examine microscope slides of single-celled and multi-celled organisms.	Application
	Describe the structure and function of major human organs.	Application
	Describe how body systems work together.	Comprehension, application
9-12	Relate the parts of a cell to its function.	Application
	Describe how cells replicate and transfer genetic information.	Comprehension
	Discuss the function of: proteins (enzymes and hormones), carbohydrates, lipids, and nucleic acids.	Comprehension
	Analyze and debate principles of genetic engineering: procedures, uses, and ethical implications.	Comprehension

According to the MLR outlined in Table 2.2, students enrolled in BIO100 (as recent high school graduates) were expected to have reached the level of comprehension and application of cell content. BIO100 course objectives were intended to build on the previously outlined standards.

2.1.3. What content knowledge are high school students expected to know about cell structures and functions?

The 2007 Maine *Learning Results* distinguish the performance indicators and descriptors of cell knowledge among four grade groups: pre-K-2, grades 3-5, grades 6-8, and grade 9-diploma. During elementary school (K-5), students learn about parts and wholes of living things (such as organs make up humans), the basic needs of life (e.g., all living things need food), and later they are introduced to cells. Middle-school students are expected know the hierarchy of structural organization in organisms (such as cells, tissue, organs, and organisms) and the functional similarities and differences between the structural levels. In high school, students learn about the molecular level of cells, interactions between cells and their surroundings, and how systems and processes occur , at the molecular level, that impact the entire organism (MDOE, 2007). Table 2.3 explicitly states the Maine high school learning standards for cells.

Table 2.3. Maine performance indicators and descriptors for students in grades 9-diploma learning about cells, section E3 (MDOE, 2007).

Section	Cell: performance indicators and descriptors
a.	Describe the similarities and differences in the basic functions of cell membranes and of the specialized parts within cells that allow them to transport materials, capture and release energy, build proteins, dispose of waste, communicate, and move.
b.	Describe the relationship among DNA, protein molecules, and amino acids in carrying out the work of cells and how this is similar among all organisms.
c.	Describe the interactions that lead to cell growth and division (mitosis) and allow new cells to carry the same information as the original cell (meiosis).
d.	Describe ways in which cells can malfunction and put an organism at risk.
e.	Describe the role of regulation and the processes that maintain an internal environment amidst changes in the external environment.
f.	Describe the process of metabolism that allows a few key biomolecules to provide cells with necessary materials to perform their functions.
g.	Describe how cells differentiate to form specialized *systems* for carrying out life functions.

The NGSS disciplinary standards are similar to the MLR content standards when it comes to cellular content and core ideas. Where the two guidelines differ is the

emphasis on conceptual understanding and application. The NGSS emphasize crosscutting of cellular concepts (e.g., systems, models, energy and matter, structure and function, and stability and change) by developing models, investigations, and solutions. The NGSS also includes clarification statements and assessment boundaries that clearly state concepts teachers should emphasize and examples of questions that teachers should avoid because they emphasize rote knowledge rather than the desired concepts. An example of an assessment boundary is that students should not identify steps of mitosis. Table 2.4 outlines NGGS's cellular learning standards (NGSS, 2013; NRC, 2012).

HS-LS1-2 is the most pertinent NGSS standard for this thesis. The learning standard suggests students need to use models to show their comprehension of systems and subsystems within a multicellular organism. The NGSS standard does not want students to be assessed on their ability to name specific cells or tissue, but rather be assessed on their ability to describe how cells interact within tissue to provide specific functions (e.g., smooth muscle cells regulate blood flow by contracting and narrowing the vessel walls to provide the proper amount of blood to other tissue throughout the body) (NGSS, 2013).

Table 2.4. NGGS high school learning standards: From Molecules to Organisms: Structures and Processes (NGSS, 2013; NRC, 2012). HS-LS1-2 is most pertinent to this thesis and is bolded.

Section	Cell Learning Standards
HS-LS1-1	Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins, which carry out the essential functions of life through systems of specialized cells.
HS-LS1-2	**Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.**
HS-LS1-3	Plan and conduct an investigation to provide evidence that feedback mechanism maintain homeostasis.
HS-LS1-4	Use a model to illustrate the role of cellular division (mitosis) and differentiation in producing and maintaining complex organisms.
HS-LS1-5	Use a model to illustrate how photosynthesis transforms light energy into stored energy.
HS-LS1-6	Construct and revise an explanation based on evidence for how carbon, hydrogen, and oxygen from sugar molecules may combine with other elements to form amino acids and/or other large carbon-based molecules.
HS-LS1-7	Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in the new compounds are formed resulting in a net transfer of energy.

2.1.4. What crosscutting concepts are especially applicable to learning about cells?

To gain a deeper understanding of cells in the living context, students are expected to comprehend crosscutting science concepts, such as systems and system models, energy and matter, structure and function, stability and change, and scale. The goal of these crosscutting concepts standards is to suggest learning progression and to establish connections between big ideas that students and scientists alike can use to better understand their surroundings (Duncan & Rivet, 2013). The science concepts are established in the national and state standards and NGSS to provide consistency between science disciplines (AAAS, 1989 and 1993; NGSS, 2013; NRC, 1996 and 2012; and MDOE, 2007). The crosscutting science concepts will be reviewed here in terms of how they relate to cells and what students are expected to understand by the time they complete high school.

2.1.4.1. Systems and models

High school students are expected to explain, analyze, and give examples of natural systems, such as cells and their role in the body. When students enter college, they should recognize that organisms can be studied at varying depths. Middle school students learn about the hierarchical subsystems: the organism level, organ, tissue, cell, organelles, molecules, elements, and atoms (MDOE, 2007; NGSS, 2013).

Students should understand that different types of cells have commonalities and differences in structure and function that make up subsystems, comprising larger systems (i.e., tissue, organs, and organisms) allowing them to function as a unit (AAAS, 1989; MDOE, 2007). Cells vary in function and size to form specialized systems for carrying out life functions. Cells also having common threads, such as: basic cellular processes (i.e., protein synthesis, extraction of energy, and replication), utilization of proteins to carry out the cellular processes (i.e., cell repair, movement of molecules, genetic replication, and building and regulating cellular molecules), and DNA for instructional codes to create proteins and amino acids (AAAS, 1989).

Physical models need to be used for students to comprehend the scale of cells and their variation (NRC, 2012). Physical models are used to represent a phenomenon that may have size, time, or financial constraints. The model can be scaled in size to make it convenient for learning about the modeled phenomenon, such as cells (AAAS, 1989). Models are used to learn about how things work. Incorrect ideas may be acquired if the model is observed without a discussion of the model's usefulness and limitations (AAAS, 1993; MDOE, 2007).

2.1.4.2. Scale

Maine high school students are expected to apply their understanding of scale of natural phenomena to explain biological systems (AAAS, 1993; MDOE, 2007). Comprehending the scale of cells poses two teaching challenges: 1) the extremely small size of most cells is difficult to conceptualize because the magnitude is outside of our everyday experiences (AAAS, 1993) and 2) cells can vary in size. For example, a red blood cell is small, at approximately 7.5 micrometers, which allows it to circulate through capillaries carrying oxygen to every cell in the body, while a nerve cell can span the distance of an animal's entire leg to provide sensory and motor input to the distal limb. Comprehension of the scale of cell size ties into the comprehension of how cellular subsystems fit together to create the larger biological system.

2.1.4.3. Constancy and change

High school students are expected to understand that systems and entities can change in detail, but remain the same in general (e.g., individual cells constantly divide, grow, and die, yet the organism remains) (MDOE, 2007). A system appears to be unchanging, but viewed at the molecular level will show the continuous activity of the molecules in that system (AAAS, 1993). Constancy and change encompasses the dynamic nature of cells and their inner factory-like environment, which is hard to visualize because of their microscopic size. Animated models and use of microscopes to observe living cells can help convey the constant motion that occurs within and among cells (Saunders & Taylor, 2014).

2.2. What alternative conceptions do students hold when learning about cells?

High school students are expected to learn about structural components and life-supporting functions of cells and learn how those structures and functions of cells manifest in living organisms. Research indicates that students construct and maintain alternative conceptions that stay with them until they are confronted with an observation that doesn't fit their mental model (Saunders & Taylor, 2014). Some alternative conceptions of cells will be reviewed here.

Dreyfus and Jungwirth (1989) found that 16-year-old Israeli students had several gaps in knowledge about cell structures and functions. Students' alternative conceptions were identified and grouped into categories based on the source, such as "outside of the classroom," "overgeneralization of science knowledge," and "inadequate vocabulary usage" (Dreyfus and Jungwirth, 1989) (Table 2.5).

Table 2.5 High school biology students' alternative conceptions identified by Dreyfus and Jungwirth (1989).

TYPE	SOURCES	EXAMPLES
B	Everyday, non-classroom experiences	The "smart membranes" alternate conception, e.g., cells 'knows' what to take in and get rid of
C	Overgeneralization or inference of scientific knowledge	Specialization of cells in protein and energy production was an overgeneralization of the fact that specific cell types do specialize
D	Scientific term is replaced by a careless word	The cell membrane 'controls' the intake of materials: the membrane is then understood as being able react to stimuli it receives

Students have more difficulty comprehending abstract cell concepts than acquiring content knowledge. Learning the names and functions of cell structures is concrete for those that can be seen with a microscope (Dreyfus & Jungwirth, 1989). Even with the use of microscopes, comprehending the scale of cells is an abstract idea that may be hard for students who are just beginning to develop an ability to think in abstractions – to imagine structures and relationships that they cannot concretely see, or compare to their scale of perception. Research indicates many elementary students hold the incorrect belief that organisms contain cells, missing the idea that organisms are made of cells, which are their simplest functional and structural units (AAAS, 1993).

Biology instruction that emphasizes vocabulary and memorization of cells structures can hinder students' acquisition of conceptual understanding and their excitement towards science (AAAS, 1993, Tanner and Allen, 2002). Although vocabulary and structures are important to know, memorizing cell structures or cell types is not a sufficient means of meeting learning standards; the concepts are expected be examined at a deeper level (NRC, 2012, Tanner and Allen, 2002).

Research suggests that students may hold many alternative conceptions about cell structures and functions. Students' alternative conceptions are presented in light of the unifying science themes outlined by the Maine Learning Results (MDOE, 2007).

2.2.1. Alternative conceptions about systems and models

Students often have the view that the whole is like its parts and vice versa (Brosnan, 1990). Brosnan categorizes elementary children's stereotypical views of the nature of change as common-sense view or scientific view. The common sense belief would be the properties of an object are the same as those parts that make it up. Elementary students are taught to dismiss their common-sense idea and adopt the scientific view that parts make up a whole that has different features than the individual parts (Brosnan, 1990).

Brosnan's common sense theory is evident in the alternate conception that elephant cells are larger than mouse cells, which Dreyfus and Jungwirth (1989) found in 16-year-old students in the Israeli study that thought the animal's size dictates the size of its cells. Students are expected to understand that cell size is not dependent on the organism's size, but rather on the limitations to surface-area-to-volume ratio (AAAS, 1989). Cells require a large surface-area-to-volume ratio to effectively have particles diffuse into the center of the cell so cellular processes can be carried out. As cells increase in size, their volume increases at a faster rate than the surface area. Larger cells have larger volumes, so they have features that increase their surface area (i.e., enterocytes have folded cell membranes, neurons are thin and elongated) to have adequate diffusion.

When learning about systems, students of all ages tend to focus on the parts of the system rather than the interactions between those parts (Driver et al., 1985). Students are expected to know the cell structures and functions by the time they enter college. Understanding how those parts work together to create an entire organism is complex (NRC, 1996).

Because most cells are microscopic, biology instructors use abstract representations to clarify the subject matter (Lowe, 1989). Students may have difficulty extracting correct meaning from the models. Sanger, Brecheisen, and Hynek (2001) found that osmosis animations actually improved introductory undergraduate biology students understanding of particle movement, although some alternate conceptions still persisted. Models can be useful when learning about abstract concepts, but the model limitations need to be made explicitly obvious to the students to avoid misinterpretation.

Properties that are not shared between a real cell and a model (such as shape and motility) often lead to alternate conceptions (Thiele and Treagust 1991, Thagard 1992). Alternate conceptions can form when students are unaware of the models' boundaries (Dyche et at. 1993, France 2000). Students typically think the models are physical copies of reality and can be distracted by the concrete attributes of the model, which can result in misconceptions about the real nature of the object (Brook et al., 1983; Grosslight et al., 1991). Students' perceptions of cells may be inaccurate because cells in textbooks are presented in generalized diagrams that fail to illustrate scale, variety, and the placement of the object in a larger context (Adams and Griffard, 2001).

Similar misinterpretations of model were seen with physics students. The students with minimal experience interpreting abstract representations, such as a speed vs. time graph, directly interpret compelling visual attributes. The physics students activated the *what-you-see-is-what-you-get (WYSIWYG)* cognitive structure, which produced inaccurate or low-level understanding of the graph (Elby, 2000).

Many freshmen college students are concrete thinkers and may resort to basic memorization if they are unable to manipulate abstract ideas in biology and if they lack visual imagery (Kolodiy, 1975; Treagust, 1993). In one study, forty students, ages 9-15 years old, were asked to identify or reconstruct three-dimensional cross-sectional biological images. Students encountered difficulties with shape reconstruction and did not appreciate the spatial relationships between the internal parts of a structure (Russell-Gebbett, 1984). Thiele and Treagust, believe that when students had difficulties with the abstract representations, the concept the model was trying to convey is missed and the students are unable to use the model in different contexts (Thiele and Treagust 1991, Treagust 1993).

2.2.2. Alternative conceptions about scale

Research indicates that students find it challenging to imagine the scale of how many cells create a large organism because they have no direct experiences with objects of that minute size. Students' perceptions of scale are based on everyday experience (i.e., running a mile or using a tape measure). To help students conceptualize how many cells it takes to create something large like a human being, teachers are encouraged to say millions of millions, rather than trillions of cells (AAAS, 1993).

In a study involving 215 science students, ranging from middle school to doctoral students, Tretter et al. (2006) suggest that students organize conceptions about scale into categories. According to these researchers, the more experience gained, the more detailed and sophisticated knowledge structures become and the number of size categories increases. When the scale of something is outside of their experience (either bigger or smaller), students are inclined to put everything in a broader category, typically defined by one prototype (Tretter et al., 2006). The research suggests students' comprehension of cell size is based on one prototypical cell and may not encompass the broad range of cell sizes. When students were asked to rank organisms on size, researchers discovered that students take more time ranking animals of similar sizes than those of obviously different sizes. One hypothesis for this delay in ranking is that it may be reflecting the degree of association between neurons. Specific neurons in proximity to each other are activated when students think about sizes or numbers, indicating they have similar mental representations. (Dehaene, 2002; Tretter et al.2006).

2.2.3. Alternative conceptions about constancy and change

Visualizing cells as microscopic factories and comprehending that organisms are composed of trillions of these specialized, dynamic factories can stretch the imagination of the students who are new to abstract thinking. The constancy and change of the chemical activity occurring in cells may be too complex for elementary students, so the AAAS suggest learning the molecular functions of cells in high school or beyond (AAAS, 1993).

High school and college students learn about molecular activity within and between cells, such as diffusion, osmosis, and replication of DNA. Research indicates

that students have gaps in the comprehension of molecular constancy and change that extends into college. In two studies, high school and college students demonstrated belief that when particles move from high to low concentration they move until the solutions are isotonic, then the particles stop moving. The students were found to not appreciate the continually moving nature of these microscopic cellular factories (Odom, 1995 and Zuckerman, 1993).

2.3 What questions are still unanswered by the literature?

Students entering college are expected to know the words for cell structures and their functions, as well as comprehend how crosscutting concepts of systems, scales, models, and consistency and change apply to living cells. Research indicates that high school students harbor alternative concepts about cells, but the extent to which they persist into college and upon completion of a basic biology course is not clear. My review of literature sets the stage for my three research questions:

1. How do undergraduate basic biology students perceive the dynamic nature of cells in the living context?
2. To what extent do students improve their factual content knowledge about cells and their understanding of how cells in a living context are made in basic biology?
3. Do students who appear to know facts about cells, such as the names of structural parts or chemical steps in the Krebs Cycle, also have high SAT scores and BIO100 grades?

CHAPTER 3

METHODS

3.1. Research setting

This study was conducted at The University of Maine. The students were undergraduates enrolled in a four-credit basic biology course (BIO100) offered by The School of Biology and Ecology. BIO100 includes a lecture (three credits) and laboratory (one credit) that covers fundamental topics in biology including the structure and function of cells, the molecular basis and mechanisms of genetic inheritance, concepts in evolution, mechanisms of metabolism, and basic concepts in ecology.

The course objectives were identified in the textbook, Campbell and Reece's 8th Edition, *Biology.* Each chapter of the textbook includes overall objectives and concepts that students are expected to understand upon completion of the chapter (Campbell and Reece, 2007). The textbook objectives were provided to the BIO100 students as study guides for examinations. The objectives appear to expect students to reach the Multi-structural and Relational levels of reasoning (See Appendix A).

The one-semester course is offered in the fall and spring semesters. The professor presents the course material in a lecture supported with slide presentations, in three weekly, one-hour sessions. Students also take a weekly, two-hour inquiry-based laboratory, facilitated by graduate teaching assistants (TAs). TAs guide the students, working in groups, in inquiry-based activities that often involve small experiments.

A condensed BIO100 session is also offered for one month in the summer, with a daily one-hour lecture coupled with two weekly two-hour laboratory sessions. I collected data during the summer (class size, n=40) and fall (class size, n=721) semesters in 2009.

3.2. Purpose

The purpose of this study was to: 1) identify the extent of students' conceptual understanding of cells after taking BIO100; 2) determine what gains were made in students' knowledge of cells in the beginning and at the end of taking BIO100; and 3) investigate if there was a correlation between the students' BIO100 exam scores (i.e., the formal evaluation used to assess student learning in BIO 100) and their academic performance on the SAT and overall BIO100 grade.

To identify students' perception of cells, students' ideas were classified into two types of cognitive domains: content knowledge and contextual understanding (Bloom, 1956) (Table 3.1). The NGSS crosscutting concepts are reflected in Bloom's Taxonomy at the level of comprehension and understanding.

Table 3.1. Two types of cognitive domains: content knowledge and conceptual comprehension were examined

Cognitive domain	Description	Example
Content knowledge	General and detailed knowledge about cells; i.e., basic cell vocabulary, identifying the structures and functions	Define a cell; identify specific organelles and their functions (i.e., Golgi bodies and ribosomes)
Contextual understanding (comprehension of the unifying themes in science)	Systems	Explain the similarities and differences among cells and their context within and among organisms
	Models	Describe the similarities between a cell diagram and real cells; analyze the usefulness and limitations for varying models
	Constancy and change	Understand constancy (i.e., genetic information, basic cell processes) and change (i.e., movement, differentiation) related to cells
	Scale	Understand the range of cell sizes and how they compare to other object sizes (i.e., hydrogen atom, grain of sand)

3.3. Research design overview

Three research questions were investigated in the summer and fall to determine how students' perceive cells as well as the impact of BIO100 on their comprehension of the science themes related to cells (Table 3.2).

Table 3.2. Summary of research design outlining questions and methods.

Research Questions	**Summer BIO100 (Pilot Study)**	**Fall BIO100**
At what cognitive level do BIO100 students understand cells' vary *in the context of the living organism*?	Pre- and post-instruction written surveys (n=15)	Interviews (n=10)
What gains in knowledge and contextual understanding of cells do students make during BIO100?	Pre- and post-instruction survey distributions (n=15)	Pre- and post-instruction exam normalized gains <*g*> (n=483)
Is there any correlation between how well students do on the BIO100 cell exam questions and their SAT scores and BIO100 grades?	Post-instruction exam scores vs. SAT scores and BIO100 grades (n=15)	Post-instruction exam scores and exam normalized gains <*g*> vs. SAT scores and BIO100 grade (n=10)

To assess students' content knowledge and their contextual understanding in the summer and fall 2009 BIO100 courses, I used four different data sources to measure students' cell concepts, due to differences in the course formats and timing: summer course-exams and surveys and fall practice exams and interviews (Table 3.3). The BIO100 exams were used to measure students' detailed content knowledge of cell structures and functions. The surveys and interviews also measured students' content knowledge in addition to their contextual understanding of cell structures, functions, and cell type variability. Gains in fall students' content knowledge were measured with pretests and exams.

Table 3.3 Research tools used to measure students' content knowledge and contextual understanding of cells.

Semester	Research tool	Pre/post instruction	N	Content knowledge	Contextual understanding
Summer	Course Exams	post	40	Q1-20	-
	Surveys	pre/post	15	Q1, 3-4	Q2
Fall	Practice exams	pre/post	483	Q1-4	-
	Interviews	post	10	Q1,Q2 (D.1-3)	Q2(D.4-6), Q4-5

I used different instruments in the summer and fall courses because of differences in the class size and structure. The pilot study was performed in the summer. The summer course had fewer students (n=40), but the schedule allowed me time to administer my own pre- and post-instruction surveys to assess student's contextual understanding and some general content knowledge of cells. The fall class had many more students (n=483), but because of limited flexibility in scheduling, I was not able to administer the written survey to all students, as was done in the summer. Instead, I conducted post-instruction interviews with a randomly selected sample of volunteer students, conducted outside of class.

In this chapter, the research instruments are discussed in chronological order with a description and rationale for each question, and an explanation of how responses to each question were scored and analyzed. Rubrics were used to assign quantitative scores to open-ended survey and interview responses. The rubrics were created using the framework for cognitive level of thinking based on the Structure of Observed Learning Outcomes (SOLO) Taxonomy of Biggs and Collis (1991). The SOLO Taxonomy breaks down the levels of reasoning by complexity, which fits well with the purpose of this investigation. Students' responses were assigned one of the four cognitive levels of reasoning: Pre-structural (i.e., incorrect reasoning), Uni-structural (i.e., simplistic, one-

track reasoning), Multi-structural (i.e., complete reasoning that considers several factors), and Relational (i.e., highest level of reasoning that connects multiple factors) (Biggs and Collis, 1991). To ensure that my scoring was reliable, a BIO100 laboratory instructor scored a sample of student responses and my scores matched the TA scores above 85%.

3.4. Pilot study: Summer 2009 data collection

3.4.1. Course exam questions: to assess specific content knowledge

A pilot study was conducted during the summer 2009 class, students completed four exams designed by the course instructor, as part of their course grade. I reviewed the four exams and selected all questions that pertained to cells – a total of twenty questions, fourteen from the first exam and six from the final exam (Table 3.4). The other two exams did not have any questions pertaining to cells. The exam questions assessed students' content knowledge (i.e., definitions, structures, and mechanisms pertaining to cells). The exams scores were compared to students' SAT scores and BIO100 grade.

Table 3.4 Exam questions that assessed students' content knowledge of cells in the 2009 summer semester. Several questions were duplicated in the first and final exams. The correct answers are bolded.

Exam questions	Content knowledge assessed
1. The lowest level of biological organization that can perform all the activities required for life is the... A. organelle-for example, a chloroplast. B. **cell-for example, a skin cell.** C. tissue-for example, nervous tissue. D. organ system-for example, the reproductive system. E. organism-for example, an amoeba, dog, human, or maple tree.	Cell definition
2. All of the following can be part of a prokaryotic cell *EXCEPT*... A. DNA B. RNA C. plasma membrane D. ribosomes E. **chloroplasts**	Cell type; degree of complexity of cell structures

Table 3.4. continued.

3. Which of the following is a major cause of the size limits for certain types of cells? A. The requirement for the largest volume possible to allow a cell's function. B. The difference in plasma membranes between prokaryotes and eukaryotes. C. The evolution of eukaryotes after the evolution of prokaryotes. **D. The need for a surface area of sufficient area to allow the cell's function.** E. The observation that longer cells usually have greater cell volume.	Cell size is limited by maximum surface area and minimal volume to increase accessibility of cell products
4. Which structure is the site of the synthesis of proteins that may be exported from the cell? **A. rough ER** B. lysosomes C. peroxisome D. Golgi vesicles E. nucleus	Function of rough endoplasmic reticulum
5. Under which of the following conditions would you expect to find a cell with a predominance of free ribosomes? A. a cell that is secreting proteins **B. a cell that is producing cytoplasmic enzymes** C. a cell that is constructing its cell wall or extracellular matrix D. a cell that is digesting food particles E. a cell that is enlarging its vacuole	Definition and location of free ribosomes and cytoplasmic enzymes
6. Which of the following contains its own DNA and ribosomes? A. lysosome B. vacuole **C. mitochondrion** D. Golgi apparatus E. peroxisome	Mitochondrion definition
7. Why isn't the chloroplast classified as part of the endomembrane system? A. It only has two membrane layers. **B. Its structure is not derived from the ER.** C. It has too many vesicles. D. It is not involved in protein synthesis. E. It is not attached to the outer nuclear envelope.	Definition of endomembrane system; chloroplast characteristics
8. Cells can be described as having a cytoskeleton of internal structures that contribute to the shape, organization, and movement of the cell. Which of the following is part of the cytoskeleton? A. the nuclear envelope B. mitochondria **C. microfilaments** D. lysosomes E. ribosomes	Structure of cytoskeleton
9. Which of the following is a reasonable explanation for why unsaturated fatty acids help keep any membrane more fluid at lower temperatures? **A. The double bonds form kinks in the fatty acid tails, forcing adjacent lipids to be further apart.** B. Unsaturated fatty acids have a higher cholesterol content and therefore more cholesterol in membranes. C. Unsaturated fatty acids permit more water in the interior of the membrane. D. The double bonds block interaction among the hydrophilic head groups of the lipids. E. The double bonds result in shorter fatty acid tails and thinner membranes.	Structure and properties of unsaturated fatty acids

Table 3.4. continued.

10. Which of the following is *TRUE* of integral membrane proteins? A. They lack tertiary structure. B. They are loosely bound to the surface of the bilayer. **C. They are usually transmembrane proteins.** D. They are not mobile within the bilayer. E. They serve only a structural role in membranes.	Definition of integral membrane protein and transmembrane protein
11. Which of the following is *TRUE* of the evolution of cell membranes? A. Cell membranes have stopped evolving now that they are fluid mosaics. B. Cell membranes cannot evolve if proteins do not. C. The evolution of cell membranes is driven by the evolution of glycoproteins and glycolipids. **D. As populations of organisms evolve, different properties of their cell membranes are selected for or against.** E. An individual organism selects its preferred type of cell membrane for particular functions.	Natural selection; properties of the cell membrane
12. Which of the following is a characteristic feature of a carrier protein in a plasma membrane? A. It is a peripheral membrane protein. **B. It exhibits a specificity for a particular type of molecule.** C. It requires the expenditure of cellular energy to function. D. It works against diffusion. E. It has few, if any, hydrophobic amino acids.	Structure or function of carrier protein
13. A patient has had a serious accident and lost a lot of blood. In an attempt to replenish body fluids, distilled water, equal to the volume of blood lost, is transferred directly into one of her veins. What will be the most probable result of this transfusion? A. It will have no unfavorable effect as long as the water is free of viruses and bacteria. B. The patient's red blood cells will shrivel up because the blood fluid becomes hypotonic compared to the cells. **C. The patient's red blood cells will swell because the blood fluid becomes hypotonic compared to the cells.** D. The patient's red blood cells will shrivel up because the blood fluid becomes hypertonic compared to the cells. E. The patient's red blood cells will burst because the blood fluid becomes hypertonic compared to the cells.	Red blood cell properties; definition of hypo/hypertonic; mechanisms of diffusion and concentration gradients
14. What are the membrane structures that function in active transport? A. peripheral proteins B. carbohydrates C. cholesterol D. cytoskeleton filaments **E. integral proteins**	Mechanism of active transportation
15. Under which of the following conditions would you expect to find a cell with a predominance of free ribosomes? A. a cell that is secreting proteins **B. a cell that is producing cytoplasmic enzymes** C. a cell that is constructing its cell wall or extracellular matrix D. a cell that is digesting food particles E. a cell that is enlarging its vacuole	Definition and location of free ribosomes and cytoplasmic enzymes
16. Which is one of the main energy transformers of cells? A. lysosome B. vacuole **C. mitochondrion** D. Golgi apparatus E. peroxisome	Function of a mitochondrion

Table 3.4. continued.

17. Which of the following are capable of converting light energy to chemical energy? **A. chloroplasts** B. mitochondria C. endoplasmic reticulum D. lymphocytes E. Golgi bodies	Function of a chloroplast
18. All the following can be found within a eukaryotic OR a prokaryotic cell, *EXCEPT*_____. **A. chloroplasts** B. ribosomes C. lipid membranes D. DNA E. protein	Cell type; degree of complexity of cell structures
19. What kinds of molecules pass through a cell membrane most easily? A. large and hydrophobic **B. small and hydrophobic** C. large polar D. ionic E. sugars such as glycogen	Properties of the cell membrane
20. A patient has had a serious accident and lost a lot of blood. In an attempt to replenish body fluids, an isotonic solution, equal to the volume of blood lost, is transferred directly into one of her veins. What will be the most probable result of this transfusion? **A. It will have no unfavorable effect as long as the isotonic solution is free of viruses and bacteria.** B. The patient's red blood cells will shrivel up because the new fluid is isotonic compared to the cells. C. The patient's red blood cells will swell because the new fluid is isotonic compared to the cells. D. The patient's red blood cells will dissolve because the new fluid is isotonic compared to the cells. E. The patient's red blood cells will burst because the new fluid is isotonic compared to the cells.	Definition of isotonic solution; properties of a red blood cell; mechanisms of diffusion and concentration gradients

3.4.2. Assessment of content knowledge and contextual understanding

To measure students' understanding of cells, identical surveys were administered to BIO100 undergraduate students before and after relevant instruction during the 2009 summer term. Each survey question was designed to assess a particular aspect of students' perceptions about cells in a living context, such as the size of cells relative to organisms or other components of organisms.

The survey questions were developed from assessments used in previous studies that targeted students' misconceptions about cells (Reiss and Tunnicliffe, 2001; Dreyfus and Jungwirth, 1989; and Klymkowsky and Garvin-Doxas, 2008). Each survey question is discussed in detail below. The survey was created to gain a deeper insight into student understanding that was not indicated by the BIO100 exams. The exams assessed more specific content knowledge.

On the first and last day of the course, I visited the classroom and invited the 40 students taking the class to participate in two 20-minute, in-class, written surveys; of the 40 students in the course, 15 students participated in both the survey administrations.

I reviewed and scored the open-ended responses on the written surveys according to their level of cognitive complexity. I developed a scoring rubric for each question drawing from the SOLO framework described by Biggs and Collis (1991). Scores were presented in frequency tables to summarize how students are thinking about cells before and after taking BIO100 and to what extent their perceptions may have changed by the end of the course. Each survey question and its scoring rubric are described below.

3.4.2.1. Survey question 1: Cell definition, structures, and functions

Question 1 assessed students' content knowledge of the cell definition, structures, and functions (Figure 3.1). Students were asked to define, draw, and label an animal cell. The drawings indicated students' visual perception of cells. Table 3.5 presents the scoring rubric for Question 1.

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1. During school break you decide to volunteer and go back to your middle school to help teach a fifth grade lesson on cells. To prepare for class the teacher asks you to answer the following questions below and emphasizes your explanations must be *concise, thorough,* and *clear* so the students can understand.

    a. What is a cell?

    b. Draw an animal cell. Label all the structures and identify the function for each structure.

Figure 3.1. Question 1 of the summer surveys.

Table 3.5. Scoring rubric for Question 1 of the summer surveys. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Quantitative Score	**Cell definition** *A. Identifies and describe key characteristics of cells*	**Cell drawing** *B. Draw a cell (shape)* *C. Identifies cell structures* *D. Describe the structures' functions*
Level 1 ***Pre-structural***	0	A.1 Incorrectly defines or does not define the cell (e.g., a cell is a portable phone)	B.1 Incorrectly depicts cell or not drawn (e.g., *draws a cell phone*)
			C.1 Identifies incorrect structures or none (e.g., *labels no structures*)
			D.1 Identifies incorrect functions or none (e.g., *no functions described*)
Level 2 ***Uni-structural***	1	A.2 Defines cells incompletely, identifies one characteristic (e.g., a cell the smallest unit)	B.2 Draws simple image of a round cell (e.g., *image of a circle*)
			C.2 Identifies 1 correct structure and/or does not distinguish between plant and animal cell structures (e.g., *"The animal cell has a nucleus and cell wall."*)
			D.2 Identifies correct function for 1 structure (e.g., *"The nucleus contains the genetic information."*)
Level 3 ***Multi-structural***	2	A.3 Defines cells completely, identifies multiple characteristics (e.g., a cell is an organism and is the smallest unit of life)	B.3 Draws complex image of an irregularly shaped cell (e.g., *draws a cell that is not a circle*)
			C.3 Identifies 2 or more correct structures and contains no structures found only in plant cells (e.g., *"The cell a mitochondria and cell membrane."*)
			D.3 Identifies correct functions for 2 or more structures (e.g., *"The membrane is a semi-permeable barrier that allows some particles in and out of the cell, the nucleus contains the DNA, etc.."*)
Level 4 ***Relational***	3	A.4 Defines cells completely, identifies cell types and characteristics (e.g., a cell can be an entire organism like a bacterium or the basic structural, functioning unit that makes up more complex organisms like us; we are made of specialized cells that each have specialized functions that enable us to live, for example a blood cell carries oxygen to and from other cells in our body)	B.4 Draws specific animal cell with accurate depiction of shape (e.g., *image of a long nerve cell*)
			C.4 Accurately identifies multiple cell structures with correct spatial relation with each other (e.g., *"The ribosomes are on the rough endoplasmic reticulum."*)
			D.4 Identifies correct functions for multiple structures and relates functions to overall function of the cell (e.g., *"The nucleus hold the DNA which aides the cell in division and protein synthesis; the mitochondria is the powerhouse of the cell that creates energy for cell processes."*)

3.4.2.2. Survey question 2: Contextual understanding

Question 2 evaluated students' contextual understanding of cell sizes, specialization, genetic information, and cell autonomy (Dreyfus and Jungwirth, 1989). The students were asked to respond to four statements about cells that were either true, untrue, or both, depending on the condition (Figure 3.2).

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2. Indicate whether you agree or disagree with the statements below and explain your reasoning.

A. An elephant cell is larger than a mouse cell.
B. There is a lot of specialization amongst body cells. We can thus find cells specializing in energy production and others that specialize in protein synthesis.
C. Different cells in an embryo contain different genetic information; this is why the different parts of the body are so unlike each other.
D. A single cell can be self-sufficient and survive.

Figure 3.2. Question 2 of the summer surveys.

Statement 2A was designed to measure students' understanding of cell size. Dreyfus and Jungwirth (1989) found that biology students often think that cell size is dependent on the animal size. In reality, an elephant is larger than a mouse because it has more cells. Cell size is limited by the surface area-volume ratio; a Relational response would discuss the cell size variation and limitations.

Student responses were scored by cognitive level of response (Table 3.6). The scores indicated students' understanding of cell size.

Table 3.6. Scoring rubric for Question 2A: An elephant cell is larger than a mouse cell. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Score	**Q2A. Elephant vs. mouse cells** *Compare cell size and number between animals*
Level 1 ***Pre-structural***	0	A.1 Incorrect response (e.g., *"Elephants have larger cells."*) or no response
Level 2 ***Uni-structural***	1	A.2 Response is incomplete, identifies one component (e.g., *"Animal cells are the same size."*)
Level 3 ***Multi-structural***	2	A.3 Response is complete (e.g., *"An elephant has more cells and cells are relatively the same size."*)
Level 4 ***Relational***	3	A.4 Response is complete (e.g., *"Cell size is not dependent on the size of the animal rather the ratio of surface area and volume; different types of cells in an animal have different sizes."*)

Statement 2B assessed students' ability to distinguish between: cell differentiation and universal processes that occur in all cells (i.e., cellular respiration and protein synthesis). Dreyfus and Jungwirth (1989) indicated students believed that specific cells specialized in energy production and protein synthesis.

The responses were scored using the rubric in Table 3.7. The scores indicated the degree that students understood cell differentiation and universal cell processes.

Table 3.7. Scoring rubric for survey Question 2B: There is a lot of specialization amongst body cells. Some cells specialize in energy production and others specialize in protein synthesis. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Score	**Q2B. Cell specialization** *Identifies all cells produce energy and proteins*
Level 1 ***Pre-structural***	0	B.1.1 Incorrect response (e.g., *"Cells specialize in energy production."*) or no response
Level 2 ***Uni-structural***	1	B.1.2 Response is incomplete, identifies one component (e.g., *"Cells have different functions."*)
Level 3 ***Multi-structural***	2	B.1.3 Response is accurate (e.g., *"All cells produce energy and proteins."*)
Level 4 ***Relational***	3	B.1.4 Response is accurate and complete (e.g., *"All cells produce energy and proteins as well as differentiate to perform specific functions within a system."*)

Statement 2C assessed students' ability to differentiate between the role of genetic information and cell differentiation. A misconception exists that genetic information is different among cells in an individual (Dreyfus and Jungwirth, 1989). The student with low understanding stated different genetic information accounted for the different body parts. A higher understanding would compare and contrast the roles of genetics and cell differentiation.

Table 3.8 outlines the scoring rubric for the student responses. The scores for Question 2C indicated students' understanding of the role and structure of genetic information.

Table 3.8. Scoring rubric for Question 2C: Different cells in an embryo contain different genetic information; this is why the different parts of the body are so unlike each other. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Score	**Q2C. Genetic information** *Identifies all cells in one being have the same genetic information*
Level 1 ***Pre-structural***	0	C.1 Incorrect response (e.g., *"I agree, genetic information differs between cells in one organism."*) or no response
Level 2 ***Uni-structural***	1	C.2 Response is incomplete, identifies one component (e.g., *"Cells have different genetic information due to heredity."*)
Level 3 ***Multi-structural***	2	C.3 Response is accurate (e.g., *"All cells in one being have the same genetic information."*)
Level 4 ***Relational***	3	C.4 Response is accurate and complete (e.g., *"All cells have the same genetic information . Cells differentiate to form different tissues."*)

Statement 2D assessed students' understanding of cells' autonomy. Bacteria and amoebae are single-celled organisms that are self-sufficient. Cells from a multicellular organism such as an animal cell are not self-sufficient. Either response was acceptable, but if a student referenced both, that indicated the student had a broader concept of the variability of cells (Table 3.9).

Table 3.9. Scoring rubric for Question 2D: A single cell can be self-sufficient and survive. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Score	**Q2D. Sustainability of single cells** *Identifies types of single cells that can and can't be self-sufficient*
Level 1 ***Pre-structural***	0	D.1 Incorrect response (e.g., *"Unicellular cells cannot survive."* or *"Multicellular cells can survive alone."*) or no response
Level 2 ***Uni-structural***	1	D.2 Response is incomplete, identifies one type of cell (e.g., *"A human cell cannot be self-sufficient."* or *"A prokaryotic cell can survive solo."*)
Level 3 ***Multi-structural***	2	D.3 Response is accurate, identifies cells that can and cannot be self-sustaining (e.g., *"A bacterium can survive on its own, where a red blood cell needs to be within a system to survive."*)
Level 4 ***Relational***	3	D.4 Response is complete, identifies cells that can and cannot be self-sustaining and compare cell requirements (e.g., *"A bacterium can survive on its' own in a favorable environment (i.e., adequate food source, temperature, pH). A red blood cell needs to be within a habitable system that provides adequate nutrition and in the proper temperature and pH."*)

3.4.2.3. Survey questions 3 and 4: Biology Concept Inventory

Questions 3 and 4 were designed to assess students' content knowledge of diffusion and the structure of the cell membrane (Figure 3.3). Both were multiple-choice questions used in the Biology Concept Inventory (BCI) (Klymkowsky and Garvin-Doxas, 2008). Question 3 assessed students' knowledge of the mechanism of diffusion. Question 4 asked students about the structure of a lipid bilayer and its interaction with water. The purpose of the BCI questions was to compare them with students' contextual understanding of cells to they were associated with their understanding.

3. When we want to know whether a specific molecule will pass through a biological membrane, we need to consider...

A. The specific types of lipids present in the membrane.
B. The degree to which the molecule is water soluble.
C. Whether the molecule is actively repelled by the lipid layer.
D. Whether the molecule is harmful to the cell.

4. Lipids can form structures like micelles and bilayers because of ...

A. Their inability to bond with water molecules.
B. Their inability to interact with other molecules.
C. Their ability to bind specifically to other lipid molecules.
D. The ability of parts of lipid molecules to interact strongly with water.

Figure 3.3. Questions 3 and 4 of the summer surveys. The correct answers are in bold.

3.5. Fall 2009 data collection

3.5.1. Practice exam questions: Specific content knowledge

In the fall of 2009, BIO100 students had the option to take a practice examination twice, both at the beginning and the end of the semester. The questions were created by the BIO100 instructor, and covered all the topics that were part of the BIO100 syllabus. The course instructor's intent for the practice exams was to assess students' prior knowledge of the content material, and to record students' performances before and after BIO100 instruction to track gains in understanding. The practice exams were optional and were taken in addition to the required course exams; they provided students with a glimpse of the types of questions that would be on the course exams. To encourage students to take the optional practice exams, students were awarded bonus points for each question they answered correctly. The identical exams were administered online by the Biology Media Laboratory.

The purpose my investigation was to determine if significant gains were made in students' knowledge related to cells from before to after instruction, and to determine if the exams scores corresponded with students' SAT scores and BIO100 grades. The exam questions are multiple-choice and do not ask students' to explain their reasoning; this study will shed light on the correlation between the exam scores and understanding (as indicated by survey results) to identify if students who score well on the exams also have an accurate perception of cells as they function and exist in a living system. From the practice exams, four exam questions assessed students' knowledge of cells (Table 3.10). The specific content that each question assessed is described in the succeeding sections.

Table 3.10. Practice exam questions that assess students' content knowledge of cells in the 2009 fall term. The correct answers are bolded.

Exam questions	Content knowledge assessed
1. Which of the following is NOT a characteristic of life as discussed this semester? A. All organisms are composed of at least one cell. B. All organisms reproduce. C. **All organisms store hereditary information in RNA.** D. All organisms evolve over time. E. All organisms require cellular energy.	Life definition
2. Which of the following features do prokaryotes and eukaryotes have in common? *A.* nucleus, plasma membrane, ribosomes *B.* **ribosomes, plasma membrane, cytoplasm** *C.* mitochondria, cytoplasm, plasma membrane *D.* mitochondria, ribosomes, cytoplasm *E.* ribosomes, nucleus, plasma membrane	Structures of two cell types
3. Which of the following identify the basic structure of a phospholipid? ***A.*** **2 Fatty Acids, a phosphate group, and glycerol** *B.* 2 Fatty Acids and glycerol *C.* 3 Fatty Acids and glycerol *D.* 3 Fatty Acids, a phosphate group, and glycerol *E.* 3 Fatty Acids and a phosphate group	Structure of a phospholipid
4. If a particular eukaryotic protein is destined for a location outside the cytoplasm, where will its translation occur? *A.* Inside the Golgi body. *B.* On a ribosome in the nucleus. *C.* On a ribosome floating freely in the cytoplasm. ***D.*** **On a ribosome anchored to the rough endoplasmic reticulum.** *E.* At the site where the protein is required.	Function of rough endoplasmic reticulum

3.5.1.1. Exam question 1

Question 1 assessed students' knowledge the commonalities of life that is necessary to recognize and categorize organisms. The students were required to know the cell structure responsible for storing genetic information and differentiate between DNA and RNA. DNA stores genetic information in each cell while RNA is involved in protein synthesis.

3.5.1.2. Exam question 2

Cells are classified into the two types of cells, simple prokaryotic cells (e.g., bacteria, with no nucleus) and complex eukaryotic cells (e.g., animal and plant cells with a nucleus). Knowing the difference between prokaryotic and eukaryotic cells is fundamental to understanding how cells evolved over time to carry out more specific functions and understanding the similarities between the two types identifies the essential structures cells need to function.

Question 2 required the students to distinguish between cell structures found in both prokaryotic and eukaryotic cells. The students were asked to identify three basic cell structures found in both cell types.

3.5.1.3. Exam question 3

Cell membranes are composed of phospholipids. A phospholipid is made of two fatty acids, a phosphate group, and glycerol. This molecular structure allows the cell membrane to form a barrier that regulates the movement of proteins, ions, and other molecules in and out of the cell. This is a specific fact about cells that supports the more contextual understanding that cells can regulate what comes in and goes out of them; they

can actively and selectively absorb life-supporting materials while maintaining a barrier to harmful or unnecessary substances.

Question 3 asked students to recall the structural components of a phospholipid.

3.5.1.4. Exam question 4

Question 4 tested students' knowledge of protein synthesis and spatial relationships of the structures within the cell. Translation is a stage in gene expression where protein synthesis occurs by using the genetic code as a template to create amino acid sequences. The students needed to recall where translation occurs, which is on a ribosome that is affixed to the rough endoplasmic reticulum, in the cytoplasm outside the nucleus.

3.5.2. Interviews

Interviews were conducted in the Fall 2009 semester to gain deeper insight into BIO100 students' level of conceptual understanding of cell structure and function commonalities and variability. The summer pilot study assisted with the creation of the interview questions. The interviews are similar to the summer surveys and assess broader concepts that the exams do not.

To select interviewees, the instructor randomly selected fifty BIO100 students and invited them to participate in interviews. Of the fifty invited, ten students volunteered. Each interviewee participated in a thirty-minute interview that took place outside of class time in the Biology Department's conference and laboratory rooms in Murray Hall.

I interviewed the ten students individually, outside of class, after the completion of the lesson in lecture that was about cells. The interviews were videotaped with written consent from each student (see full IRB application, Appendix B). The outlined interview script (Figure C.1.) is in Appendix C.

Each interview began with the interviewee responding to a written questionnaire about cells that was similar to Question 1 of the summer survey. The interviewees were given approximately ten minutes to complete the first two questions of the questionnaire in writing. (The interview recording began after they completed their drawing of a cell, after Question 2). During the interview, the students answered the five questions on paper and verbally explained their reasoning. A scripted protocol was used as a guide for the interviewer to orally prompt students to elaborate on their responses; each question's protocol is presented below.

The interviews were recorded and transcribed using © 2010 Amazon Mechanical Turk. To characterize students' cognitive level of thinking, the responses were scored using a rubric based on the SOLO Taxonomy of Biggs and Collins (1991).

3.5.2.1. Interview question 1: Defining a cell

In Question 1, students were asked to define a cell (Figure 3.4). The purpose of Question 1 was to determine at what depth students describe what a cell is, when given an open-ended question about it.

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1. What is a cell?
   In reference to the building block of life: How would you define life?

Figure 3.4. Question 1 of the interview questionnaire. The scripted interview protocol questions are italicized.

Defining a cell can be a difficult task because cells are so variable in size, function, and needs. A cell is the smallest unit of life, but cells vary and size and can be large (i.e., a chicken egg). A single cell can be an organism that does not require other cells to live and function, but multiple cells that make up a multi-cellular organism require surrounding cells in order to live (e.g., a red blood cell is not self-sufficient like a bacterium). A typical biology textbook defines a cell as:

> "…the structural and functional unit of all known organisms. It is the smallest unit classified as living; the '*building block of life*'" (Campbell et al, 2008).

To score the responses to this question, the complexity of reasoning was considered to determine the depth students are thinking about what cells are. Relational-level response is indicated with a complete, in-depth reply that identifies essential qualities that make a cell a cell, with a description of cell types and examples (Table 3.11). A Multi-structural response included multiple characteristics (i.e., smallest unit of life, organism, building block, makes up our body). Students in BIO100 are expected to have a response that is exceeds a Uni-structural score. A Uni-structural response would include only one of the characteristics noted above.

Table 3.11. Interview Question 1 scoring rubric. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Quantitative Score	**A. Cell definition** *1. Identifies and describe key characteristics of cells*
Level 1 ***Pre-structural***	0	A.1 Incorrectly defines or does not define the cell (e.g., *"A cell is a portable phone that I text my friends with."*)
Level 2 ***Uni-structural***	1	A.1 Defines cells incompletely, identifies one characteristic (e.g., *"A cell is the smallest unit."*)
Level 3 ***Multi-structural***	2	A.1 Defines cells completely, identifies multiple characteristics (e.g., *"One cell can make up an organism and is the smallest unit of life."*)
Level 4 ***Relational***	3	A.1 Defines cells completely, identifies cell types and characteristics (e.g., *"A cell can be an entire organism like a bacterium or the basic structural, functioning unit that makes up more complex organisms like us; we are made of specialized cells that each have specialized functions that enable us to live, for example a blood cell carries oxygen to and from other cells in our body."*)

3.5.2.2. Interview question 2: Cell drawing and description of structures and functions

Question 2 assessed students' content knowledge of cell structures, their spatial relationships within the cell, and their functions. The students were asked to draw and identify basic structures that make up cells, and the functions of those structures -- concepts they were required to know upon completion of the BIO100 course.

To learn how students perceived variation among different types of cells, students were asked to elaborate on their drawing of a cell. I asked this question to see how well students understood that cells can vary widely from a typical illustration of a cell in a textbook, which is usually simplistic and generalized, and lacks the portrayal of structural and motile differences in specific types of cells. The scripted interview protocol questions investigated students' ability to think beyond the generalized cell model to discuss real cells found in an organism (Figure C.2.). The students' drawings and responses were scored by their complexity to indicate students' level of understanding of cell variability and the limitations of models when used to depict cells (Table 3.12).

Table 3.12. Interview Question 2 scoring rubric. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Quantitative Score	**2. Cell drawing** *A. Draw a cell (shape)* *B. Identifies cell structures* *C. Describe the structures' functions* *D. Recognizes generalities of cell model* *E. Identifies and compare cell types* *F. Identifies moving components*
		B.1 Identifies incorrect structures or none (e.g., *labels no structures*)
		C.1 Identifies incorrect functions or none (e.g., *no functions described*)
		D.1 Does not recognize the cell model is generalized, bound to specifics (e.g., *"The cell model is a specific animal cell."*)
		E.1 Unable to identify specific cells found in animals (e.g., *"I can't recall any specific animal cells."*)
		F.1 Incorrect response or none (e.g., *"The animal cell is rigid and nothing is moving in or out of the cell."*)
Level 2 ***Uni-structural***	1	A.2 Draws simplified image of a round cell, generalize shape (e.g., *image of a circle*)
		B.2 Identifies 1 correct structure and/or does not distinguish between plant and animal cell structures (e.g., *"The animal cell has a nucleus and cell wall."*)
		C.2 Identifies correct function for 1 structure (e.g., *"The nucleus contains the genetic information."*)
		D.2 Unable to distinguish between generalized cell model and real cells found in the body (e.g., *"The generalized cell is found in the body."*)
		E.2 Identifies 1 specific cell in the body (e.g., *"A red blood cell is a specific cell found in the body."*)
		F.2 Identifies particles are moving in and out of the cell but cell structures are rigid, generalize only in terms of one aspect (e.g., *"Waste and food are the only things moving in and out of the cell, the cell itself and the organelles are stationary."*)
Level 3 ***Multi-structural***	2	A.3 Draws image of an irregularly shaped cell, suggesting cell shape can vary (e.g., *draws a cell that is not a circle*)
		B.3 Identifies 2 or more correct structures and contains no structures found only in plant cells (e.g., *"The cell has a mitochondria and cell membrane."*)
		C.3 Identifies correct functions for 2 or more structures (e.g., *"The membrane is a semi-permeable barrier that allows some particles in and out of the cell. The nucleus contains the DNA."*)
		D.3 Recognizes the cell model is generalized and not found in the body (e.g., *"This model is general and is not a specific cell found in organisms."*)

Table 3.12. continued.

Level 3 ***Multi-structural***	2	E.3 Identifies 2 or more specific cells (e.g., *"Red blood cells and skin cells are specific animal cells."*)
		F.3 Identifies some cells, organelles, and particles are able to move, but unaware of the movement's significance (e.g., *"Red blood cells move through the body, vesicles move inside cells, and proteins are transported in and out of cells."*)
Level 4 ***Relational***	3	A.4 Draws specific animal cell with accurate depiction of shape, able to extend beyond generalized cell model (e.g., *image of a long nerve cell*)
		B.4 Accurately identifies multiple cell structures with correct spatial relation with each other (e.g., *"The ribosomes are on the rough endoplasmic reticulum."*)
		C.4 Identifies correct functions for multiple structures and relates functions to overall function of the cell (e.g., *"The nucleus hold the DNA which aides the cell in division and protein synthesis; the mitochondria is the powerhouse of the cell that creates energy for cell processes."*)
		D.4 Recognizes the cell model is generalized, not found in the body, and compare generalized cell to specific cells (e.g., *"The cell model is not found in the body, rather it is a simplified and generalized teaching tool created for students. Specific animal cells have the same structures present in the model, yet cells have specialized functions, impacting the shape, motility, and cellular products yielded."*)
		E.4 Identifies multiple specific cells and compares the structures and functions (e.g., *"Animal red blood cells are lacking nuclei and many organelles thus making them small flexible disks with depressed centers to maximize traveling capabilities to transport oxygen in the body using protein-iron complexes in the cytoplasm. Nerve cells are long (giraffe's neuron can be 15ft) thin cells to cover large areas to detect external stimulus and transmit electric signals between other neurons. Neurons lack organelles that are necessary for cell division so they are long-living and do no divide. Muscle cells contract to allow the organism to move. Muscle cells contain multiple nuclei and many mitochondria due to the high energy requirements."*)
		F.4 Identifies specific cells, organelles, and particles are able to move and what drives the movement (e.g., *"Red blood cell movement is powered and regulated by pressure created by the heart pumping and the dilation and constriction of the artery/vessel walls that are chemically triggered to supply oxygen all over the body. Vesicles move in animal cells by attaching to microtubule proteins and are transported along the conveyor-like structure to transport waste and nutrients. Proteins are packaged in the golgi and bud off in vesicles to participate in system-wide cellular processes."*)

3.5.2.3. Interview question 3: Impact of cell video on earlier responses

As part of the BIO100 lecture each year the BIO100 instructor typically presents a three-minute cell video titled, *The Inner Life of a Cell*. The purpose of showing the video is to raise students' awareness of the three-dimensional, dynamic and complex nature of cells. The video was created by the scientific animation company XVIVO for Harvard biology students (Bolinsky, Astrachan, and Liebler, 2006). The video takes watchers on an animated journey that starts inside a blood vessel, with red blood cells whizzing past. A white blood cell comes into view, rolling along the vessel wall that slips through into the tissue. The journey moves through a cell membrane into a cell where animated organelles carry out their functions. Cell processes occur simultaneously and give the impression the cell is a bustling, dynamic, three-dimensional factory. The animated journey through the cell is accompanied by music, with no narration, leaving room for the viewer to process the images without language. How does such a carefully crafted, animated portrayal of the industry and scale of the inner life of a cell affect how students perceive cells?

In the fall of 2009, the BIO100 instructor delayed showing the video in lecture until the interviews were completed. As part of Question 3, the interviewees watched the video and either wrote or mentally noted anything they recognized or that surprised them.

The goal of Question 3 was to document the extent to which their perception of cells changed after watching the video. After they watched the video, I asked the students to revisit their drawing of a cell (from Question 2) to see if they were able to reflect on their process of learning abstract concepts and describe how models that they have been exposed to impacted their understanding (Figure 3.5).

3. Watch a short video on the inside of an animal cell.
    a. Take note of anything that: you recognized or surprised you.
        i. *Have you seen this video before, if so where and when.*
        ii. *How does this depiction of the cell compare to models you have seen in the textbook?*

    b. *Look at your original drawing of an animal cell.*
        i. *Is there anything you would change about your representation of the cell? If so, what?*

Figure 3.5. Question 3 of the interview questionnaire. The follow-up interview questions are italicized.

Table 3.13 reviews the scoring rubric used for Question 3. The scores indicate students' level of metacognition with the use of models. The students that scored highest reflected the most on their process of learning about cells and their use of cell models and diagrams.

Table 3.13. Interview Question 3 scoring rubric. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Score	**3. Video reflection** *Reflect on video and learning impact*
Level 1 ***Pre-structural***	0	V.1 Irrelevant/no comment (e.g., *"I like movies."*)
Level 2 ***Uni-structural***	1	V.2 Identifies some structures in the video, discussed only one aspect and did not reflect on video's impact on cell perception (e.g., *"In the video I saw a membrane and nucleus."*)
Level 3 ***Multi-structural***	2	V.3 Discusses several independent aspects of the video, i.e., structures seen and how the video impacts perception of cells (e.g., *"In the video I saw the organelles in the cell like the mitochondria and nucleus. I did not realize so many things were moving around in the cell."*)
Level 4 ***Relational***	3	V.4 Discusses several factors and related the aspects to other model i.e., structures seen, how the video impacts perception of cells (pros and cons), compared video to other models of cells (e.g., *"In the video I saw the organelles in the cell like the mitochondria and nucleus. The video helped me visualize the cell processes with all the structures moving around. The video was complex and labels would help me identify the structures. The video model was more complex and dynamic than the cell diagram in the textbook."*)

3.5.2.4. Interview question 4: Cell size ranking

Question 4 tested students' contextual understanding of cell size and was based on a question created by Dreyfus and Jungwirth (1989). Dreyfus and Jungwirth's (1989) study indicated many students have difficulty perceiving cell size because most cells are microscopic. Question 4 asked students to rank the animal cell they drew relative to other objects (Figure 3.6).

4. Rank the sizes. In order to understand the size of your cell you have drawn, state whether the following is greater than, equal to, or less than. Explain your reasoning for each.

   Cell _____ Grain of sand

   Cell _____ Bacterium

   Cell _____ Hydrogen atom

   Cell _____ Protein

   Now rank the following from smallest to largest: the cell you drew, a bacterium, grain of sand, hydrogen atom, and protein.

   a. *Which cell that you have drawn in Question 2, are you choosing to rank?*
   b. *A bacterium is singular for bacteria.*
   c. *In response to cell<sand: How did you conclude the cell was smaller than the grain of sand?*
      i. *In response to the cell is microscopic: Are all cells are microscopic?*

Figure 3.6. Question 4 of the interview questionnaire. The scripted interview protocol questions are italicized.

The interview protocol for Question 4 sought to see how well students grasp how much cells can vary in size in the real world. The size ranking in Question 4 is dependent on the type of animal cell chosen by the student. The scoring rubric outlines the response parameters for each cognitive level of reasoning (Table 3.14).

Table 3.14. Interview Question 4 scoring rubric. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Score	**4. Size ranking** *A. Compare and rank size of cell to other items* *B. Identifies broad range of cell size*
Level 1 ***Pre-structural***	0	A.1 Incorrect/no ranking (e.g., *"Sand<hydrogen<protein<cell<bacterium"*)
		B.1 Incorrect (e.g., *"All cells are the same size."*) or no response
Level 2 ***Uni-structural***	1	A.2 Ranking is incomplete, focuses on one aspect: size and unaware of composition (e.g., *"Protein<hydrogen<bacterium<cell<sand"*)
		B.2 Overgeneralization in one aspect of size (e.g., *"All cells are microscopic."*)
Level 3 ***Multi-structural***	2	A. 3 Ranking is correct, considers two factors: size and composition (e.g., *"Hydrogen<protein<bacterium<cell<sand"*)
		B. 3 Recognizes cells can be different sizes, but unaware of examples (e.g., *"My cell could be larger than a grain of sand or smaller.")*
Level 4 ***Relational***	3	A. 4 Ranking is correct, recognizes items make-up each other, compare rankings of several types of cells, realize ranking is dependent on type of cell (e.g., *"Hydrogen<protein<bacterium<blood cell<sand< chicken egg"*)
		B. 4 Recognizes cells vary in size from large to small with examples (e.g., *"An elephant's nerve cell could be larger than sand where my skin cell would be smaller."*)

3.5.2.5. Interview question 5: Awareness of state of knowledge in field about cells

Question 5 examined students' awareness of current research about cells in a Likert-scale-style question (Figure 3.7). The purpose of the question was to see how well students understand what is known and what is not known about cells.

5. State to what extent you agree or disagree with the following statement and explain your reasoning.

There still remain cell components with unknown functions that are in need of further research.

Strongly Agree	Somewhat Agree	Somewhat Disagree	Strongly Disagree
Explanation: *d. Why do you think this? In the classroom, do you discuss what aspects of cells need further research?*			

Figure 3.7. Question 5 of the interview questionnaire. The follow-up interview protocol questions are italicized.

A Pre-structural response would state no research is necessary, we know everything about cells. A Uni-structural response is that more research is needed because we cannot possibly know everything about cells. In a Multi-structural response, the student identified an area of that needs further research but they are unable to relate to current cellular research. A Relational response would include examples of areas in need of further research and examples of current cell research being conducted (Table 3.15).

Table 3.15. Interview Question 5 scoring rubric. The student response examples are demonstrative of a typical response that would be scored at that level.

Complexity of response	Score	**5. Research beliefs** *Indicate beliefs about cell research*
Level 1 ***Pre-structural***	0	B.1 Incorrect (e.g., *"We know everything there is to know about cells."*) or no response
Level 2 ***Uni-structural***	1	B.2 Incomplete response (e.g., *"You can't know everything about something."*)
Level 3 ***Multi-structural***	2	B.3 Complete response, identifies unknown aspects of cells (e.g., *"The exact function of centrioles is not known, but scientist think they play a role in cell division and spindle formation."*)
Level 4 ***Relational***	3	B.4 Complete response, identifies unknown aspects of cells with examples of current research (e.g., *"The function of the mitochondria is well known, but scientists at The Jackson Laboratory are using high-powered microscopes to determine the shape. It is thought to be oblong, but researchers are discovering mitochondria are comprised of many spindles and they can vary in shape."*)

3.6. Data analysis: Summer and fall 2009

3.6.1. Comparison of the students surveyed (in the summer) and interviewed (in the fall) to their entire class

The SAT scores and BIO100 grades of the summer survey and fall interview participants were compared to the means for their respective classes to determine if they were academically representative of each group. To be representative of the class, the participant had to be within two standard deviations from the class mean. The means and standard deviations were calculated in Microsoft® Excel (2007).

The SAT scores and BIO100 grades were obtained from the Office of Student Records, according to approval from the Institutional Review Board (IRB). The BIO100 letter grades were converted to numeric grades using the grade point average (GPA) index (Table 3.16).

Table 3.16. Grade-to-GPA conversion table.

Letter Grade	Percentage Grade	GPA
A	93-100	4.0
A-	90-92	3.7
B+	87-89	3.3
B	83-86	3.0
B-	80-82	2.7
C+	77-79	2.3
C	73-76	2.0
C-	70-72	1.7
D+	67-69	1.3
D	63-66	1.0
D-	60-62	0.7
F	below 60	0.0
W	withdrew	0.0

3.6.2. Evidence for gains in cell content knowledge and contextual understanding

Because of differences in course format and timing, the research instruments that were used and the type of gains that were measured were different in the summer and fall semesters. In the fall, the students' content knowledge gains were determined based on the multiple-choice practice exams. In the summer, gains in students' content knowledge and contextual understanding as assessed by the written surveys were unable to be calculated because the SOLO Taxonomy rubric scores were not quantifiable because the score numbers are arbitrarily assigned. Instead, the difference between the percent of

students in the Pre- and Uni-structural categories from pre- and post-instruction were calculated.

For the fall exam questions, I scored student responses and calculated the total percentage of correct responses for the instrument pre- and post-instruction for each student. The normalized gains (<*g*>) were calculated to determine the change in each student's score from before and after the course; the equation for <g> is: (post% - pre%) ÷ (100 – pre%).

Normalized gain is preferred over absolute gain (G = post% - pre%) because it takes into account the student's performance on the pre-instruction exam administration and what the student is able to gain in the post-instruction exam administration.

To determine if the normalized gains were significant, one-tailed *t*-tests were conducted using Systat®v12.0. The null hypotheses was that the normalized gains equal zero, (i.e., students did not make any gains in understanding) which would be *rejected* if the *p*-values were equal to or less than 0.05.

3.6.3. Indicators of biology performance

Pearson correlation matrices were created to determine the degree of association between students' exam scores, gains made in BIO100, SAT scores, reason for BIO100 enrollment (requirement of major or to satisfy a general education requirement), and BIO100 grades (Table 3.17).

Table 3.17. Comparisons made in the Pearson correlations matrices to connect indicators of biology performance.

Items	Summer 2009 data source	Fall 2009 data source
Exam scores	Exam Q1-20	Post-instruction exam Q1-4
Gains from pre- to post-BIO100	-	<g> exam Q1-4
SAT scores	SAT math and verbal	SAT math and verbal
BIO100 enrollment requirement	BIO100 required or not	BIO100 required or not
BIO100 grade	BIO100 grade	BIO100 grade

The Pearson's correlation coefficient, ρ, indicates the degree of association between two variables and can range from +1 to -1. As Pearson's ρ value approaches +1 or -1 the correlation is high (either positive or negative); as the value approaches zero it is low (Figure 3.8).

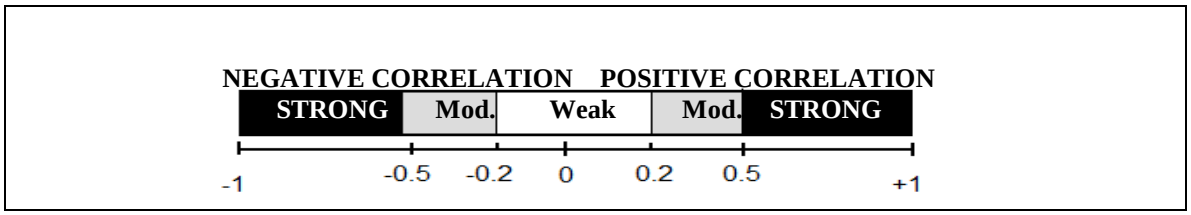


Figure 3.8. Interpreting Pearson's correlation coefficient strength (Urdan, 2001). The coefficient categories are strong, moderate, and weak.

3.7. Institutional Review Board approval for research with human subjects

The University of Maine's Intuitional Review Board (IRB) approved the methods used in this study to conduct research using human subjects. A copy of the IRB application can be found in Appendix B. The surveys and interviews were voluntary and the subjects were informed of their rights and risks involved. The IRB approved an amendment to the original IRB that allowed me to access the 2009 BIO100 students' pre- and post-test scores, SAT scores, majors, and final BIO100 grades. Following analysis, by December 2010, original identifying data was destroyed to protect the identities of the participants. Participants' insights and cooperation were greatly appreciated and made my study possible.

CHAPTER 4

RESULTS

The results of the fall and summer investigations are presented in this chapter. The students' exam and qualitative assessment (interview and survey) scores were entered into a Microsoft® Excel (2007) spreadsheet along with their SAT scores, BIO100 grades, and majors. The scores were analyzed using the statistical program Systat® v12.0.

4.1. Pilot study: Summer 2009 results

4.1.1. Were the summer survey participants academically representative of the class?

Before analyzing the survey results, I determined whether or not the students who participated in the survey (n=15) were scholastically representative of the entire BIO100 summer class (n=40). SAT scores (verbal, math, and total) and BIO100 grades for each of the 15 participants fell within two standard deviations from the class mean (Figure 4.1). I interpret this to mean that the group sampled is scholastically representative of the entire summer class.

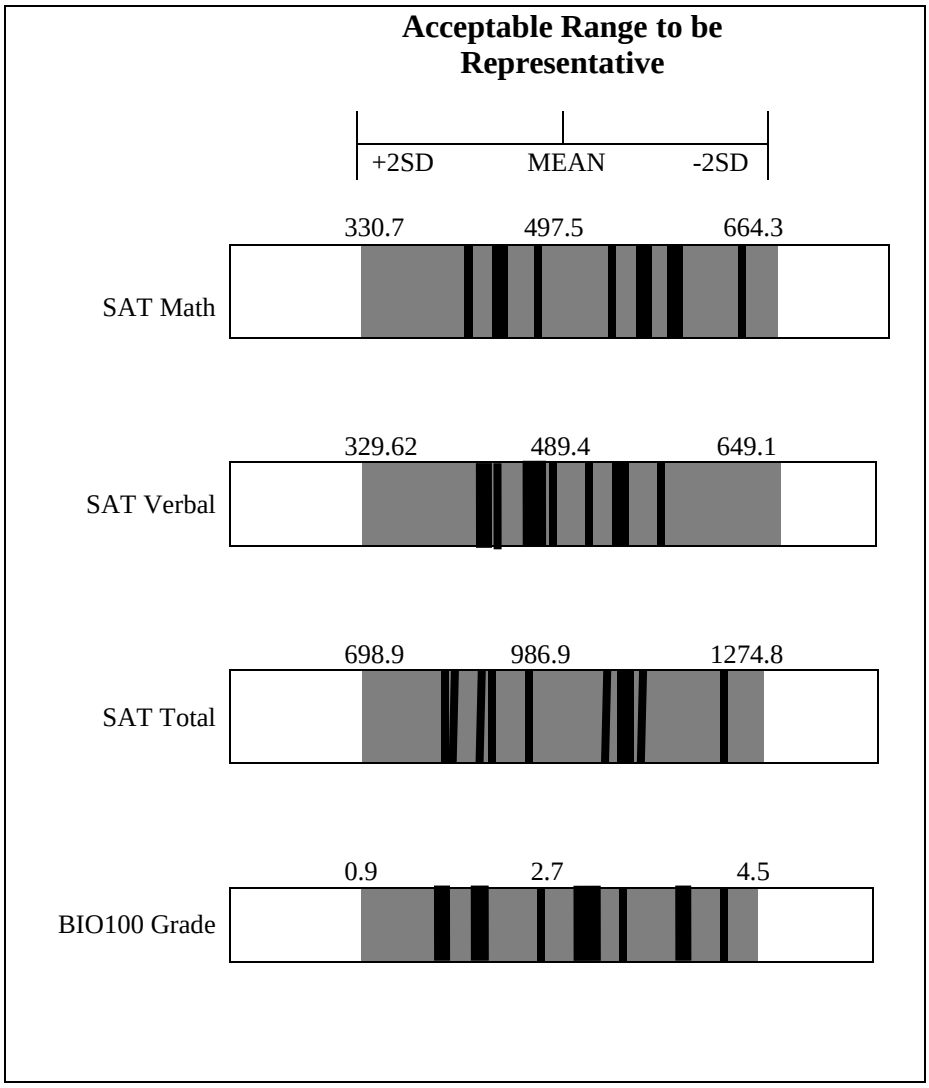


Figure 4.1. Comparison of survey participants' individual SAT score and BIO100 grades to the 2009 summer class mean scores. The participants' scores fell within two standard deviations from the class mean.

4.1.2. How did summer students perform on the BIO100 exam that assessed their cell content knowledge?

The summer exam questions were gathered from the first and final exams to measure students' content knowledge of details related to cell structures and functions (Table 3.4). The mean score for the summer BIO100 class was 71% (n=40). The students' responses for each of the twenty exam questions are reported in Table 4.1.

Table 4.1. Distribution of students' responses to the summer exam questions (n=40). Correct answers are bolded.

	Summer exam questions	Post instruction
1.	The lowest level of biological organization that can perform all the activities required for life is the...	
A.	organelle-for example, a chloroplast.	5%
B.	**cell-for example, a skin cell.**	**93%**
C.	tissue-for example, nervous tissue.	3%
D.	organ system-for example, the reproductive system.	0%
E.	organism-for example, an amoeba, dog, human, or maple tree.	0%
2.	All of the following can be part of a prokaryotic cell *EXCEPT*...	
A.	DNA	5%
B.	RNA	0%
C.	plasma membrane	10%
D.	ribosomes	5%
E.	**chloroplasts**	**80%**
3.	Which of the following is a major cause of the size limits for certain types of cells?	
A.	The requirement for the largest volume possible to allow a cell's function.	5%
B.	The difference in plasma membranes between prokaryotes and eukaryotes.	3%
C.	The evolution of eukaryotes after the evolution of prokaryotes.	8%
D.	**The need for a surface area of sufficient area to allow the cell's function.**	**85%**
E.	The observation that longer cells usually have greater cell volume.	0%
4.	Which structure is the site of the synthesis of proteins that may be exported from the cell?	
A.	**rough ER**	**78%**
B.	lysosomes	8%
C.	peroxisome	0%
D.	Golgi vesicles	15%
E.	nucleus	0%
5.	Under which of the following conditions would you expect to find a cell with a predominance of free ribosomes?	
A.	a cell that is secreting proteins	8%
B.	**a cell that is producing cytoplasmic enzymes**	**35%**
C.	a cell that is constructing its cell wall or extracellular matrix	35%
D.	a cell that is digesting food particles	15%
E.	a cell that is enlarging its vacuole	8%
6.	Which of the following contains its own DNA and ribosomes?	
A.	lysosome	3%
B.	vacuole	3%
C.	**mitochondrion**	**90%**
D.	Golgi apparatus	5%
E.	peroxisome	0%
7.	Why isn't the chloroplast classified as part of the endomembrane system?	
A.	It only has two membrane layers.	10%
B.	**Its structure is not derived from the ER.**	**63%**
C.	It has too many vesicles.	0%
D.	It is not involved in protein synthesis.	15%
E.	It is not attached to the outer nuclear envelope.	13%
8.	Cells can be described as having a cytoskeleton of internal structures that contribute to the shape, organization, and movement of the cell. Which of the following is part of the cytoskeleton?	
A.	the nuclear envelope	5%
B.	mitochondria	13%
C.	**microfilaments**	**68%**
D.	lysosomes	3%
E.	ribosomes	13%

Table 4.1. continued.

9.	Which of the following is a reasonable explanation for why unsaturated fatty acids help keep any membrane more fluid at lower temperatures?	
A.	**The double bonds form kinks in the fatty acid tails, forcing adjacent lipids to be further apart.**	**73%**
B.	Unsaturated fatty acids have a higher cholesterol content and therefore more cholesterol in membranes.	5%
C.	Unsaturated fatty acids permit more water in the interior of the membrane.	3%
D.	The double bonds block interaction among the hydrophilic head groups of the lipids.	18%
E.	The double bonds result in shorter fatty acid tails and thinner membranes.	3%
10.	Which of the following is *TRUE* of integral membrane proteins?	
A.	They lack tertiary structure.	10%
B.	They are loosely bound to the surface of the bilayer.	23%
C.	**They are usually transmembrane proteins.**	**50%**
D.	They are not mobile within the bilayer.	8%
E.	They serve only a structural role in membranes.	10%
11.	Which of the following is *TRUE* of the evolution of cell membranes?	
A.	Cell membranes have stopped evolving now that they are fluid mosaics.	5%
B.	Cell membranes cannot evolve if proteins do not.	8%
C.	The evolution of cell membranes is driven by the evolution of glycoproteins and glycolipids.	10%
D.	**As populations of organisms evolve, different properties of their cell membranes are selected for or against.**	**72%**
E.	An individual organism selects its preferred type of cell membrane for particular functions.	5%
12.	Which of the following is a characteristic feature of a carrier protein in a plasma membrane?	
A.	It is a peripheral membrane protein.	23%
B.	**It exhibits a specificity for a particular type of molecule.**	**51%**
C.	It requires the expenditure of cellular energy to function.	8%
D.	It works against diffusion.	13%
E.	It has few, if any, hydrophobic amino acids.	5%
13.	A patient has had a serious accident and lost a lot of blood. In an attempt to replenish body fluids, distilled water, equal to the volume of blood lost, is transferred directly into one of her veins. What will be the most probable result of this transfusion?	
A.	It will have no unfavorable effect as long as the water is free of viruses and bacteria.	3%
B.	The patient's red blood cells will shrivel up because the blood fluid becomes hypotonic compared to the cells.	13%
C.	**The patient's red blood cells will swell because the blood fluid becomes hypotonic compared to the cells.**	**72%**
D.	The patient's red blood cells will shrivel up because the blood fluid becomes hypertonic compared to the cells.	10%
E.	The patient's red blood cells will burst because the blood fluid becomes hypertonic compared to the cells.	3%
14.	What are the membrane structures that function in active transport?	
A.	peripheral proteins	3%
B.	carbohydrates	10%
C.	cholesterol	3%
D.	cytoskeleton filaments	21%
E.	**integral proteins**	**64%**
15.	Under which of the following conditions would you expect to find a cell with a predominance of free ribosomes?	
A.	a cell that is secreting proteins	6%
B.	**a cell that is producing cytoplasmic enzymes**	**83%**
C.	a cell that is constructing its cell wall or extracellular matrix	3%
D.	a cell that is digesting food particles	3%
E.	a cell that is enlarging its vacuole	6%

Table 4.1. continued.

16.	Which is one of the main energy transformers of cells?	
A.	lysosome	3%
B.	vacuole	6%
C.	**mitochondrion**	**86%**
D.	Golgi apparatus	3%
E.	peroxisome	3%
17.	Which of the following are capable of converting light energy to chemical energy?	
A.	**chloroplasts**	**97%**
B.	mitochondria	0%
C.	endoplasmic reticulum	0%
D.	lymphocytes	0%
E.	Golgi bodies	3%
18.	All the following can be found within a eukaryotic OR a prokaryotic cell, *EXCEPT*_____.	
A.	**chloroplasts**	**80%**
B.	ribosomes	11%
C.	lipid membranes	6%
D.	DNA	0%
E.	protein	3%
19.	What kinds of molecules pass through a cell membrane most easily?	
A.	large and hydrophobic	0%
B.	**small and hydrophobic**	**89%**
C.	large polar	3%
D.	ionic	6%
E.	sugars such as glycogen	3%
20.	A patient has had a serious accident and lost a lot of blood. In an attempt to replenish body fluids, an isotonic solution, equal to the volume of blood lost, is transferred directly into one of her veins. What will be the most probable result of this transfusion?	
A.	**It will have no unfavorable effect as long as the isotonic solution is free of viruses and bacteria.**	**77%**
B.	The patient's red blood cells will shrivel up because the new fluid is isotonic compared to the cells.	6%
C.	The patient's red blood cells will swell because the new fluid is isotonic compared to the cells.	6%
D.	The patient's red blood cells will dissolve because the new fluid is isotonic compared to the cells.	6%
E.	The patient's red blood cells will burst because the new fluid is isotonic compared to the cells.	6%

The percentage of students that answered each question correctly is reported for each exam question in Table 4.1. Most students (80% of the class or higher) were able to identify the definition or function of a cell, mitochondria, chloroplast, and cell membrane; recognize the structures of prokaryotic cells; and knew that surface area limits cell size.

The summer exam results indicate that a larger portion of students (50% or more) struggled with the exam questions pertaining to proteins (Q5, Q10, Q12). After instruction, only half of the summer students were able to identify characteristics of

integral membrane proteins (Q10) and carrier proteins (Q12). Only a third of the class knew the function of free ribosomes on the first prelim (Q5). Due to the students' low success with Question 5 the question was in the final exam (Q15). On the final, a larger portion of the class (83%) identified the function of free ribosomes.

4.1.3. What levels of complexity are students' content knowledge and contextual understanding of cells as assessed by the summer pre- and post-instruction surveys?

The summer surveys were scored according to the cognitive complexity of students' responses using a framework modified for each question using the SOLO Taxonomy of Briggs and Collins (1991). The levels of complexity, from less to more complex are: Pre-structural, Uni-structural, Multi-structural, and Relational.

4.1.3.1. Summer survey question 1: Content knowledge

Question 1 of the summer survey measured students' ability to define a cell, draw an animal cell, and label structures in their drawing. The question was broken down into four parts: the cell definition (1A), the drawing of the cell (1B), and identified cell structures (1C) and functions (1D) (Figure 4.2).

The percentage of students in the post-instruction survey that scored at the Uni-structural or Pre-structural levels were as follows: 53% of students for the cell definition (1A), 54% of students for the drawing of the cell (1B), and 14% of students for identifying cell structures (1C) and 73% of students for functions (1D). Approximately half of those surveyed scored at the lower level of complexity when they defined (e.g., a Uni-structural response only included one aspect of the definition, "cells are the basic unit of life") and drew a cell (e.g., drew a simplistic, round image of a cell). The students labeled more structures after BIO100 than before, with approximately 86% of the students in the post-instruction survey scoring at the Multi-structural or Relational level. A third of the students moved from identifying no structures to labeling multiple ones. The high amount of Pre-structural responses for identifying cells were due to many students chose not to identify the functions. The movement of responses from pre- to post-instruction for individual students is displayed in Figure 4.3.

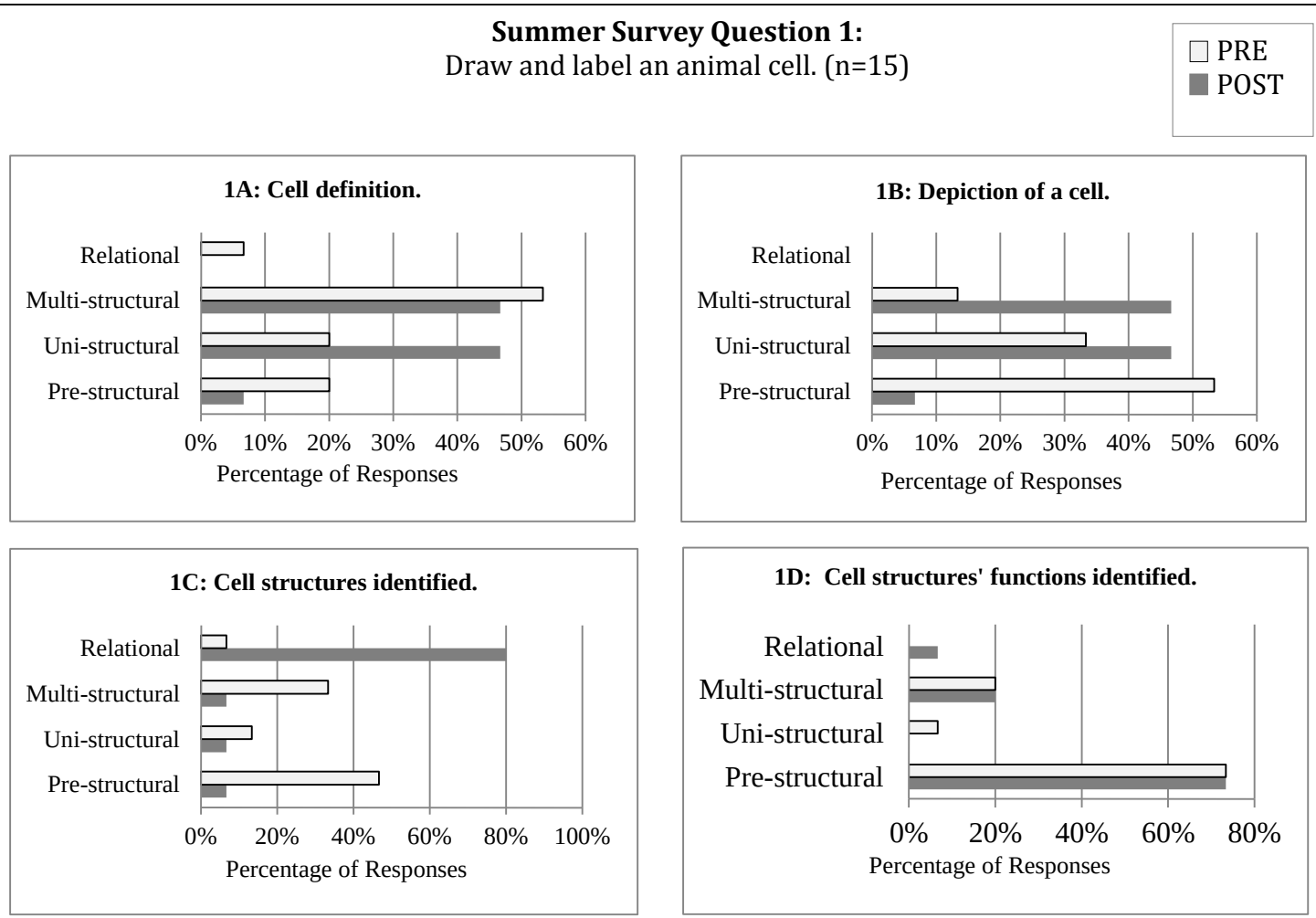


Figure 4.2 Percentage of student responses categorized by complexity of response for Question 1 of the pre- and post- summer survey.

Summer Survey Pre to Post Question 1. Draw and label an animal cell.

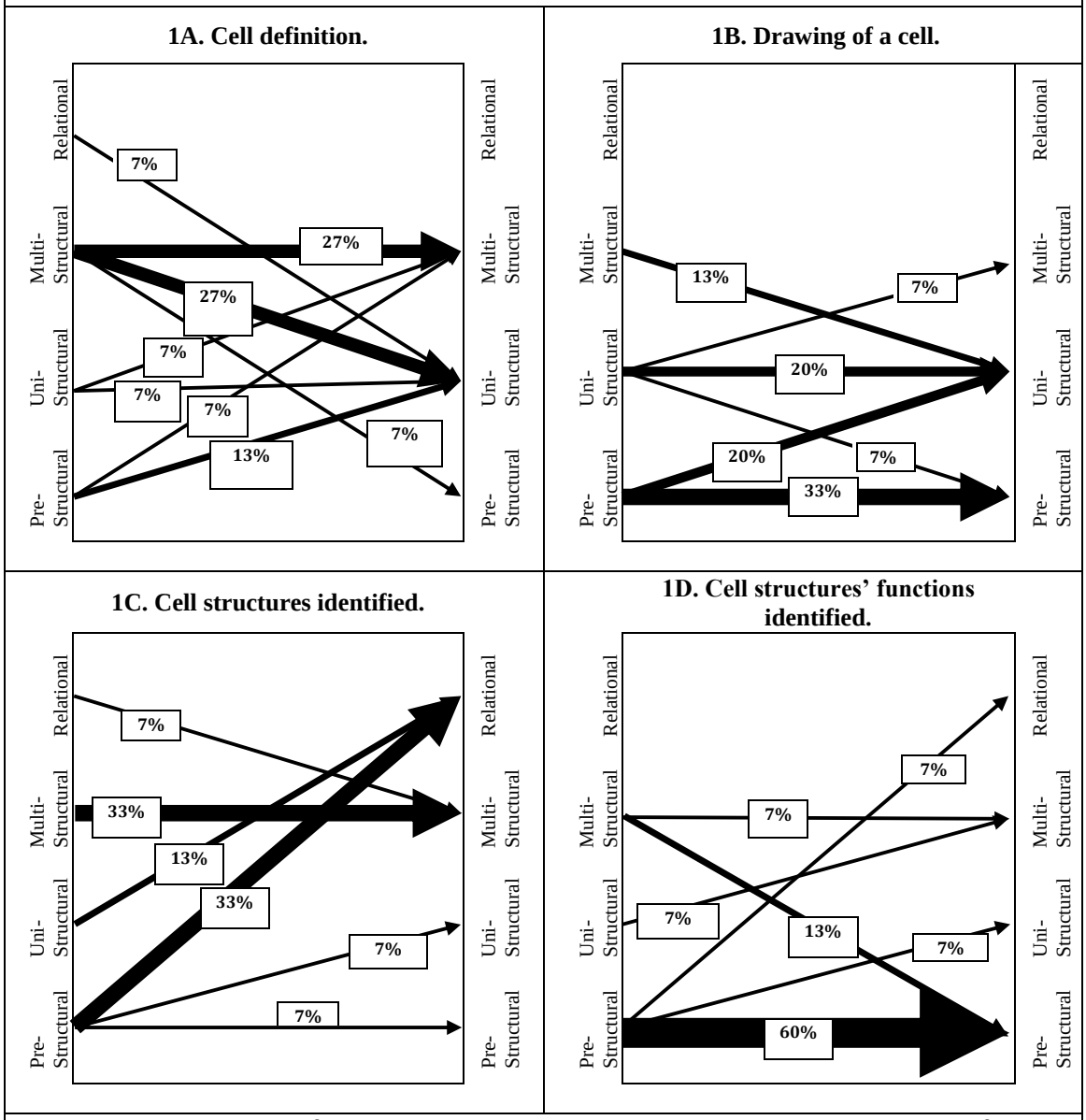


Figure 4.3. Percentage of 2009 summer student responses to Question 1 tracked from the pretest to the post-test summer surveys; arrow thickness represents frequency (n=15).

4.1.3.2. Summer survey question 2: Contextual understanding

Question 2 of the summer survey asked students to explain whether they agreed or disagreed with four statements that were based on alternative conceptions of cells (Dreyfus and Jungwirth, 1989). The four statements assessed students' understanding of cell size (A), cell commonalities (B), cell differentiation (C), and cell classification (D) (Figure 4.4). For each of the four statements, approximately 75% of the students gave a Pre- or Uni-structural response on both the pre-survey and the post-instruction survey, indicating little overall change in the cognitive level of their response (Figure 4.5).

In Question 1A, an elephant cell is larger than a mouse cell, 60% students accounted for only one factor (i.e., all cells are the same size). Twenty percent of students gave satisfactory (Multi-structural) responses and considered the cell size, as well as, the number of cells.

Question 2B assessed students' understanding of the standard cell processes that occur in all cells. Students gave mostly Pre- and Uni-structural responses. A third of the responses after instruction were incorrect (Pre-structural) and indicated students thought cells specialize in energy production or protein synthesis. After instruction, 53% of the students thought cells specialize in the body, but they did not differentiate between cell differentiation and basic processes that occur in all cells (Uni-structural). After instruction, a small number of students

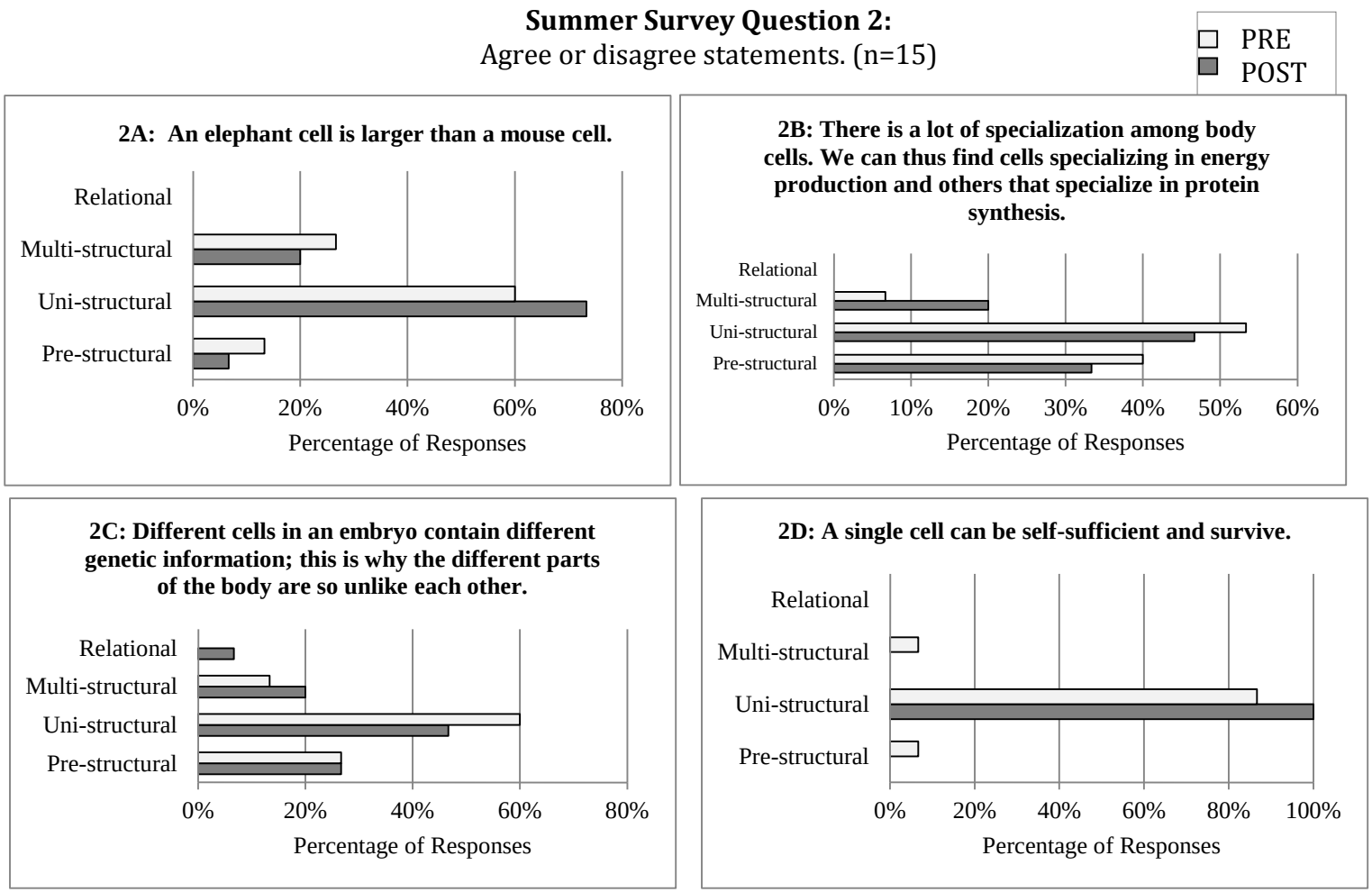


Figure 4.4 Distribution of student response complexity for Question 2 of the summer survey.

(20%) recognized that protein synthesis and energy production occurs in all cells (which is coded as a Multi-structural response). This question had room for misinterpretation because there are some cells, such as, muscle cells that have more mitochondria and produce more energy. If students explained their reasoning and provided specific examples that were correct, then they would have been scored accordingly.

Students performed slightly better in Question 2C, a statement pertaining to cell differentiation, than the other four statements. More Multi-structural (20%) and Relational responses (7%) were evident. The students with higher-level responses stated that all cells in an organism have the same genetic information and some extended their answer to discuss the role of cell differentiation. Many students (47%) incorrectly thought cells in one organism have different genetic information (Uni-structural response). The large number of Uni-structural responses indicates students have a misconception about genetic material or the students misinterpreted the question, perhaps thinking the statement was referring to genetic variation due to heredity.

Question 2D assessed students' understanding of cell type and sustainability. Most of the students (87%) only considered one type of cell (Uni-structural). After instruction, none of the students discussed the subsistence of both prokaryotic and eukaryotic cells.

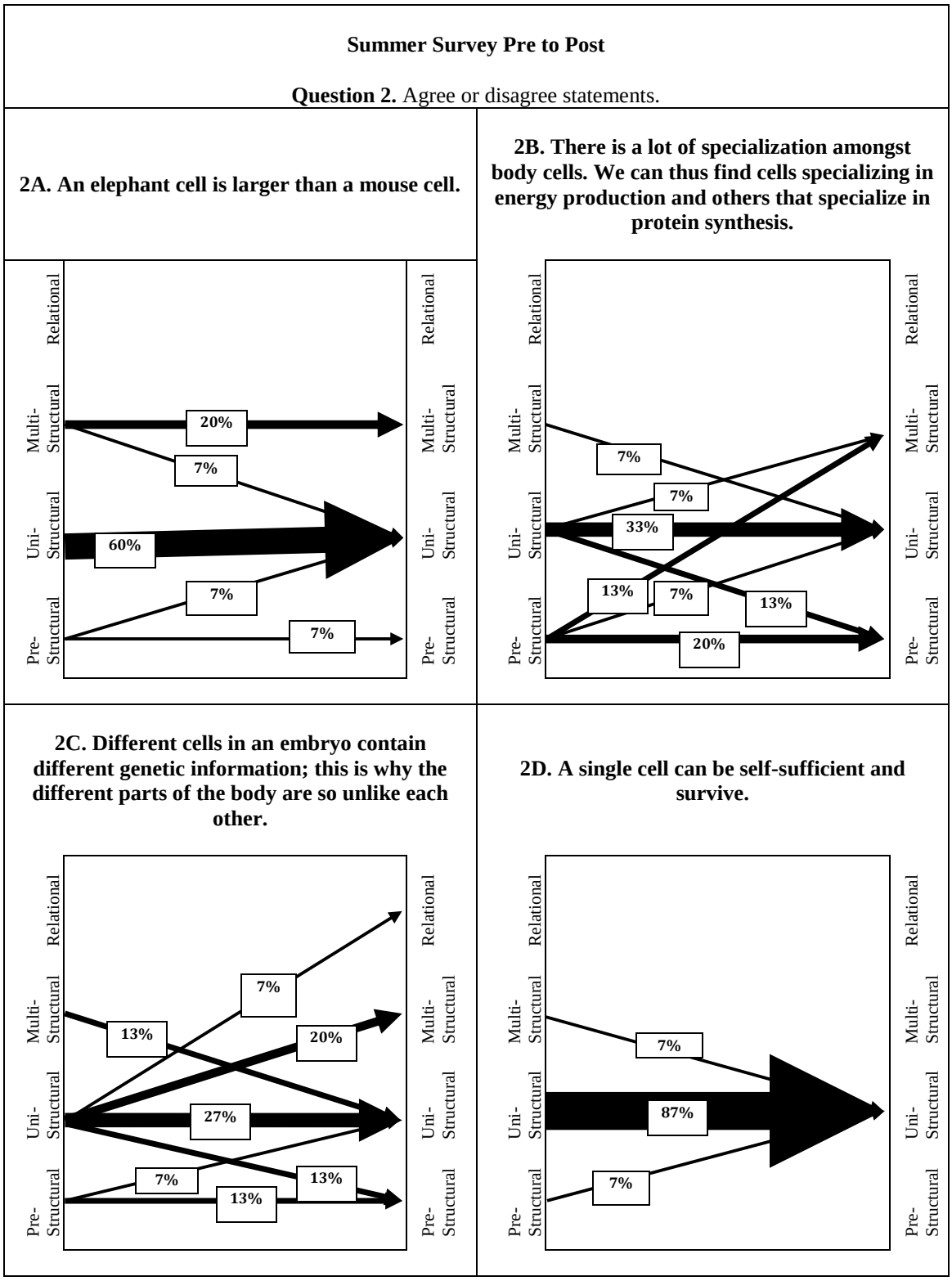


Figure 4.5 Percentage of 2009 summer student responses to Question 2 tracked from the pre- to the post- summer survey, represented by arrow thickness (n=15).

4.1.3.3. Summer survey question 3 and 4: Content knowledge

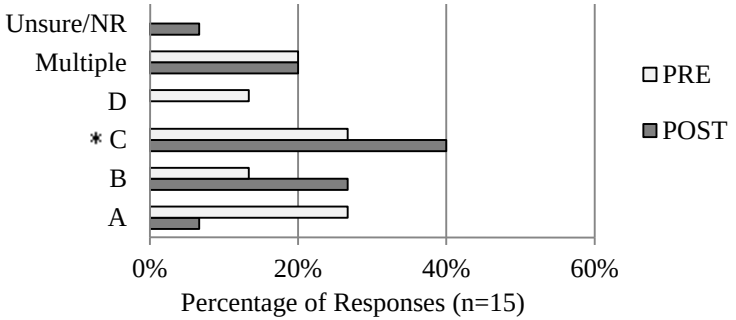
Question 3 and 4 of the summer survey assessed students' content knowledge of the mechanism of cell membranes (Figure 4.6). The two questions were multiple-choice questions from the Biology Concept Inventory (BCI) (Klymkowsky and Garvin-Doxas, 2008).

Question 3 asked students to identify what determines whether a specific molecule will pass through a biological membrane (Figure 3.3). Before instruction, 26% of the students answered correctly that the degree the molecule is actively repelled by the lipid layer determines whether it will pass through the membrane. After instruction, the percentage of students answering correctly increased to 40%. Approximately half of the students (47%) do not correctly identify the factor that influences movement and answered incorrectly before and after instruction (Figure 4.7).

Question 4 asked students about the property of lipids that allows them to form micelles and bilayers (Figure 3.3). Before and after instruction, 26% of students correctly identified the lipid molecules strong interaction with water allows for the formation of micelles and bilayers. When compared to students' performance on Question 3, there were fewer students on Question 4 that moved from the incorrect to the correct answer (13%) and more students (60%) that answered incorrectly before and after instruction (Figure 4.7). After instruction a third of the students incorrectly chose lipids' inability to bond with water molecules and another third selected lipids' ability to bind specifically to other lipid molecules. The results indicate that after instruction the students were aware that forming micelles and bilayers involve lipids and water.

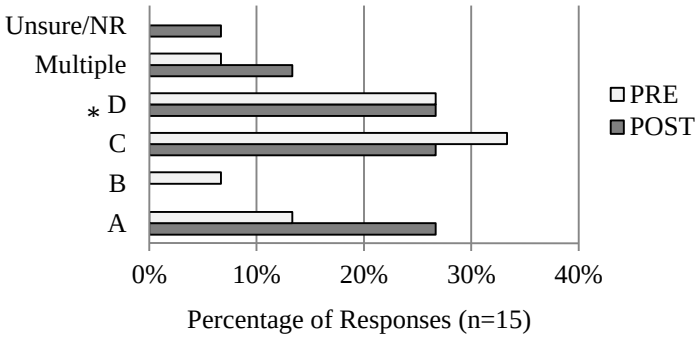
Summer Survey Question 3 & 4:
Biology Concept Inventory (n=15)

3. When we want to know whether a specific molecule will pass through a biological membrane, we need to consider...



A. The specific types of lipids present in the membrane.
B. The degree to which the molecule is water soluble.
C. Whether the molecule is actively repelled by the lipid layer.
D. Whether the molecule is harmful to the cell.

4. Lipids can form structures like micelles and bilayers because of ...



A. Their inability to bond with water molecules.
B. Their inability to interact with other molecules.
C. Their ability to bind specifically to other lipid molecules.
D. **The ability of parts of lipid molecules to interact strongly with water.**

Figure 4.6 Distribution of student response complexity for Question 3 and 4 of the summer survey.

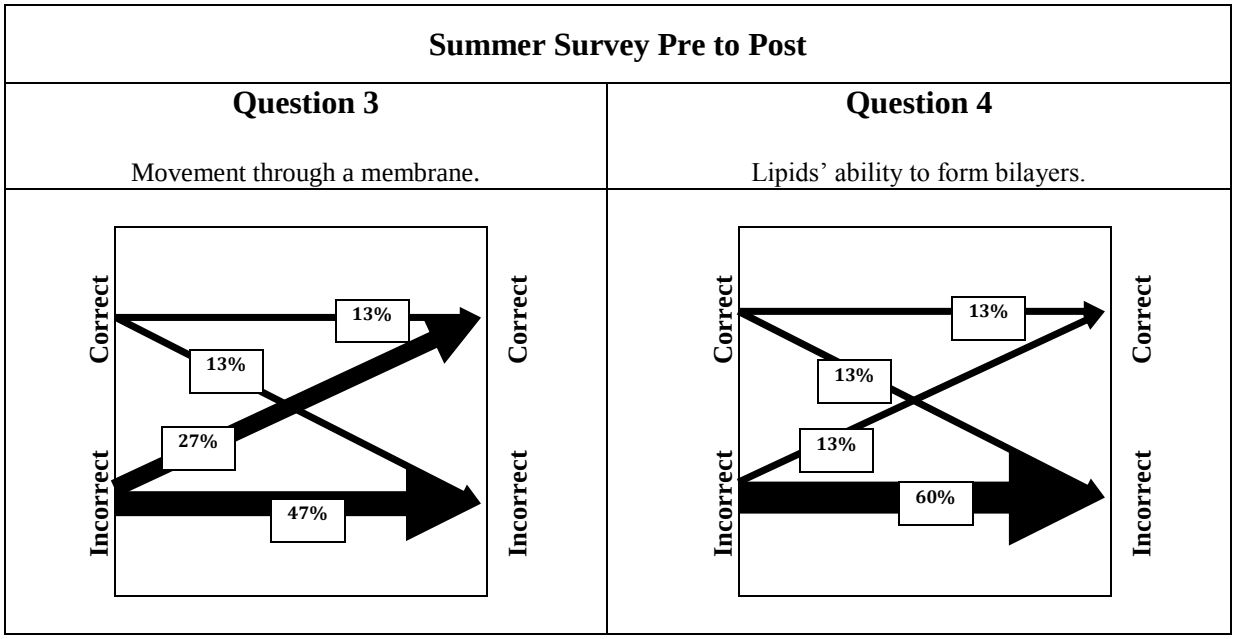


Figure 4.7. Percentage of 2009 summer student responses tracked from the pre- to the post-instruction surveys; arrow thickness represents percentage (n=15).

4.1.4. How did summer BIO100 students' content knowledge compare to SAT scores and BIO100 grades?

A correlation matrix was created to analyze the correlation between students' exam scores (exam Q1-20), SAT scores, and BIO100 grades (Table 4.2). Students' content knowledge of cells (based on the exam scores) is strongly correlated with the BIO100 grade, but not their SAT math and verbal scores. Due to the small numbers of participants in the surveys, the results may not be meaningful.

Table 4.2. Correlation coefficients of students' exam scores, SAT scores, and BIO100 grades (n=15). The bolded values indicate strong correlation (>0.5), italicized indicate medium correlation (0.3-0.49), and negative signs indicate an inverse relationship between two variables.

	SAT math	**SAT verbal**	**BIO100 grade**
Exam scores (exam Q1-20)	0.069	0.040	**0.756**

4.2. Fall 2009 results

4.2.1. Were the fall interviewees academically representative of the class?

To determine how well the interviewed students represent the entire BIO100 class, their SAT scores, BIO100 grades, and pre-instruction exam scores and normalized gains were compared individually to the mean scores for each metric for the entire 2009 BIO100 (Figure 4.8). All of the interviewees' scores fell within two standard deviations of the SAT score and BIO100 grade class means and so they are representative of 95% of the class.

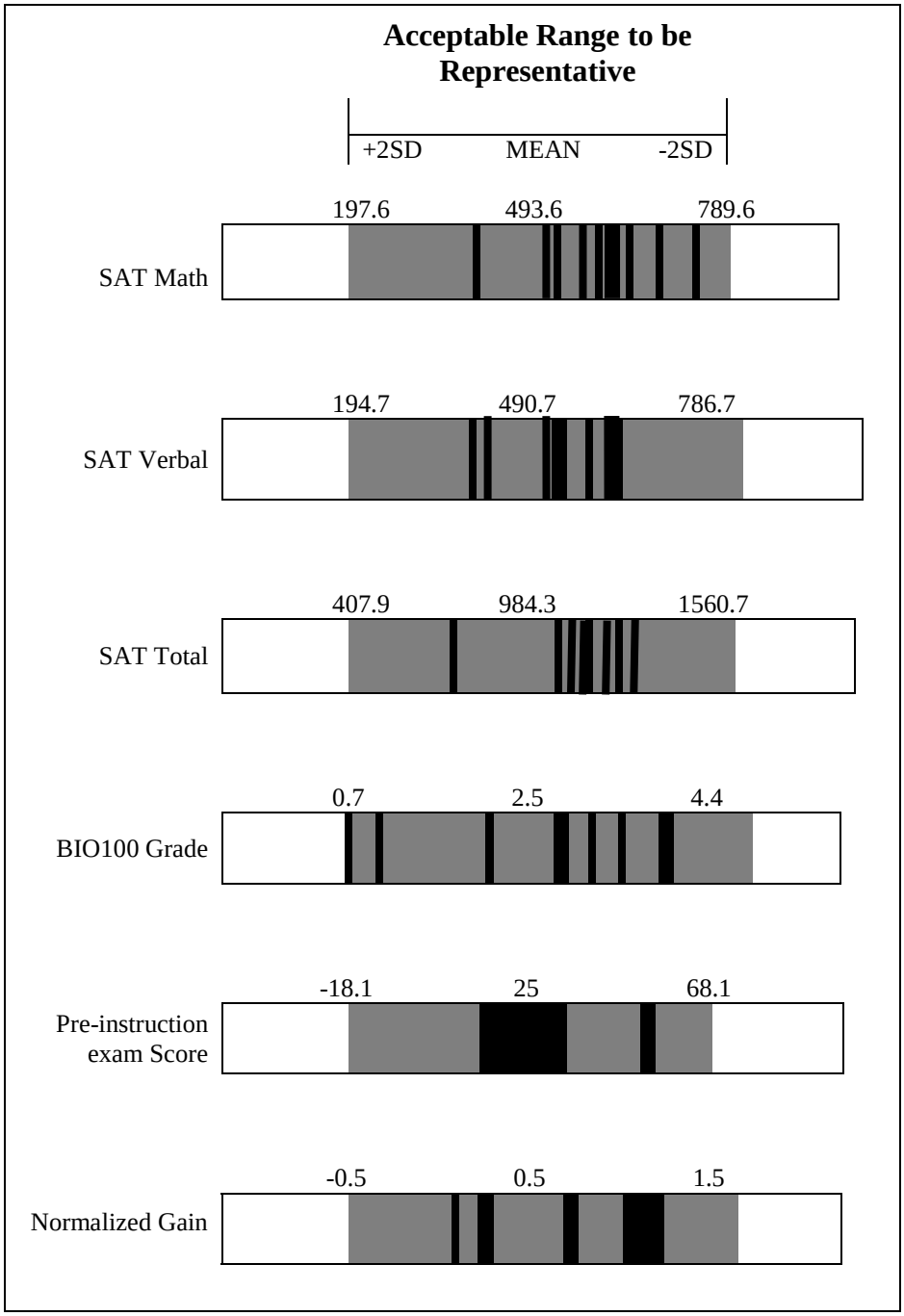


Figure 4.8. Interviewees' academic performance of the practice exam and SAT scores within the 2009 class' mean ± two standard deviations.

4.2.2. Were gains made in cell content knowledge?

The Fall 2009 practice exam results are summarized for the four exam questions (n=483); the questions are presented with the percent of student responses for each multiple-choice answer. To demonstrate the movement of student responses the students' responses from pre to post-instruction exam were tracked and recorded (Figure 4.9).

A one-sample *t*-test was used to analyze the total normalized gain for each of the four exam questions (Table 4.3). The analysis' null hypothesis was the normalized gain mean was equal to zero with a confidence level of $\alpha=0.05$. The null hypothesis was rejected; the 2009 normalized gain means for each practice exam question was significantly higher than zero ($p<0.05$).

Table 4.3. One-sample *t*-test comparing Fall 2009 normalized gains on pre- and post-instruction practice exams. Bold *p*-values indicated the means were not equal to zero ($p<0.05$).

Practice exam normalized gain (n=483)			
Exam question	**MEAN**	**SD**	***p*-VALUE**
Q1	0.423	0.495	**0.000**
Q2	0.448	0.607	**0.000**
Q3	0.405	0.622	**0.000**
Q4	0.432	0.584	**0.000**

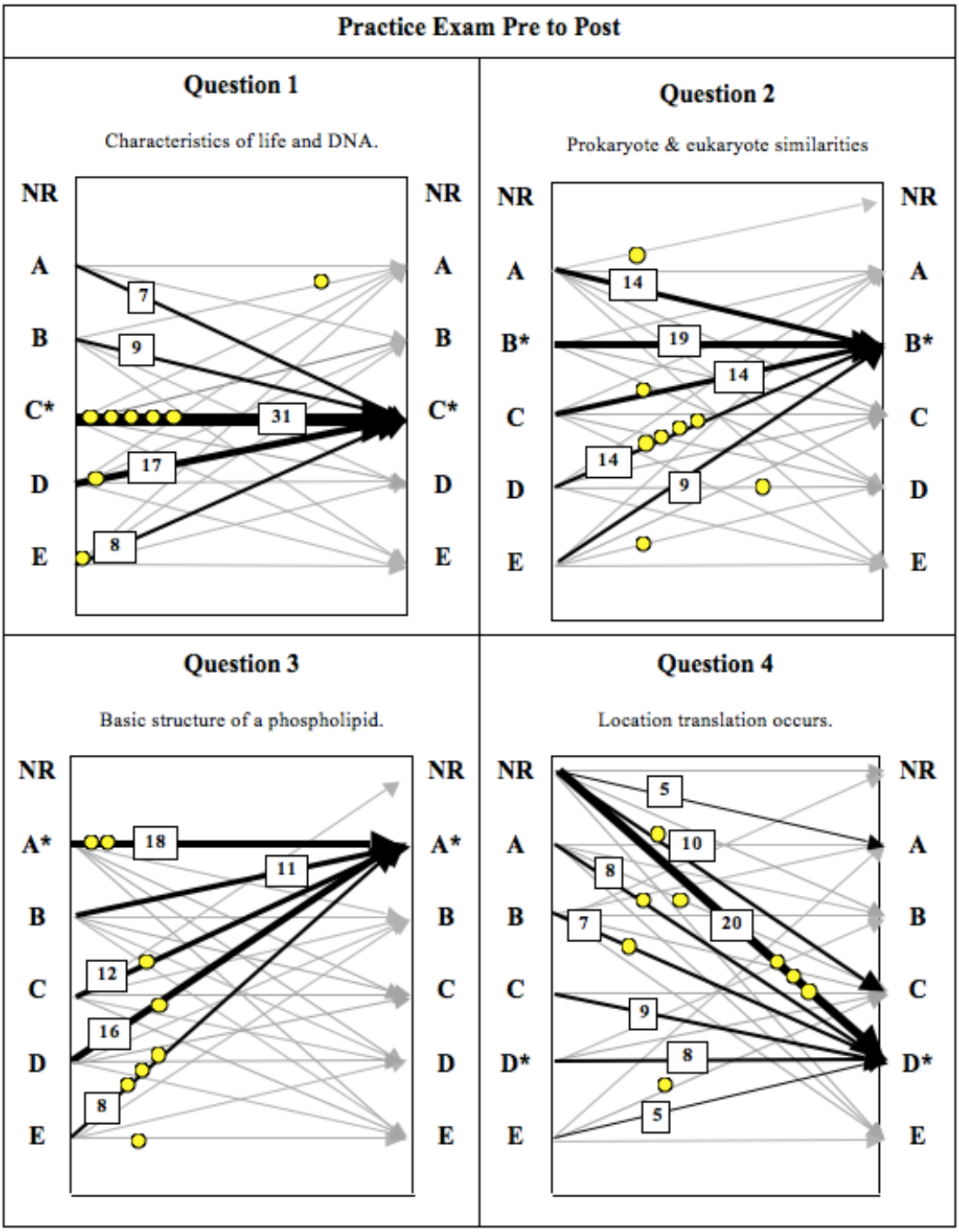


Figure 4.9 Percentage of 2009 student responses tracked from the pre- to the post-instruction practice exams (n=483). The thickness of the arrows represents the percentage of students; black arrows represent 5% or more of the class; and the circles are individual interviewees' responses.

4.2.2.1. Exam question 1

Question 1 tested students' knowledge of the commonalities all organisms have that are characteristics of life. All organisms reproduce, evolve, require cellular energy, are composed of at least one cell, and have hereditary information. Students had to identify the characteristic that was not a marker of life, (C) that all organism store genetic information in RNA rather than DNA (Figure 4.10). While 37% of students answered correctly on the pre-instruction exam, 73% answered correctly on the post-instruction exam, having a significant normalized gain (<g>= 0.571; p-value<0.001)

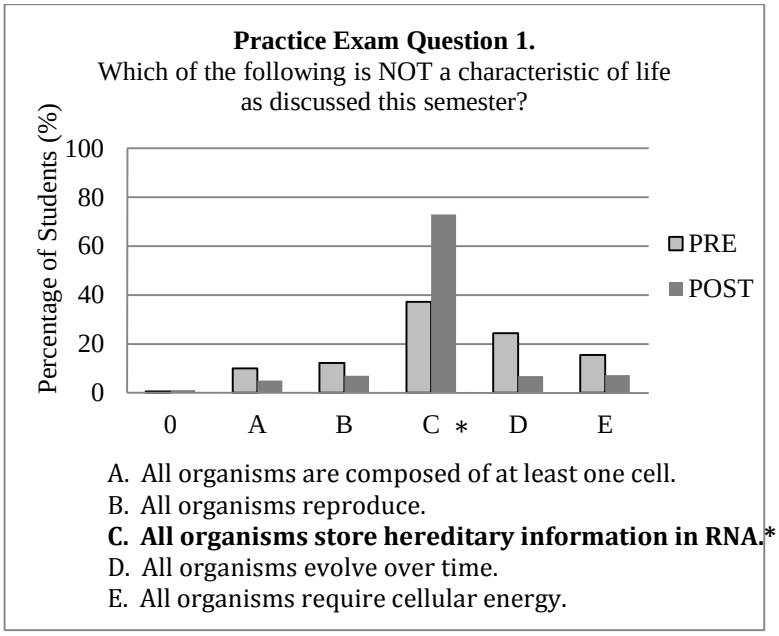


Figure 4.10. Percentage of students' responses to the fall practice pre- and post-instruction exam Question 1.

4.2.2.2. Exam question 2

Question 2 tested students' knowledge on the similarities in structure of the prokaryote and eukaryote cells. The three most basic organelles in both types of cells are: (B) ribosomes, plasma membrane, and cytoplasm (Figure 4.11). Significant gains were made before and after instruction (<g>=0.60; p-value<0.001), originally 25% of students selected the correct answer and that increased to 70% after instruction.

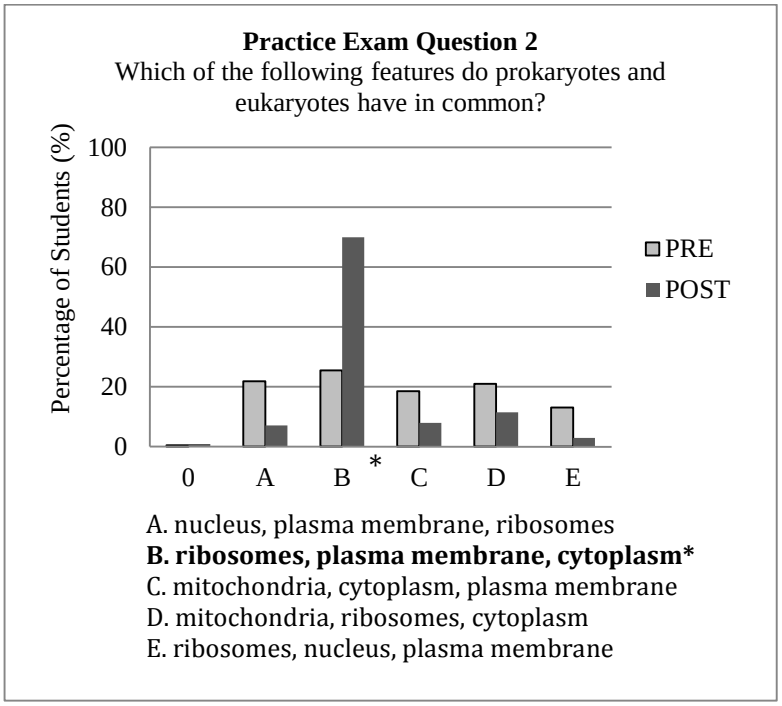


Figure 4.11. Percentage of students' responses to the fall practice pre- and post-instruction exam Question 2.

4.2.2.3. Exam question 3

Question 3 asked students to identify the three major components of a phospholipid, which are: two fatty acids, a phosphate, and a glycerol (A). In the pre-instruction exam, 25% of students chose the correct phospholipid components; that jumped to 66% after instruction (Figure 4.12). A significant gain was made from pre- to post-instruction exam (<g>= 0.547; p-value<0.001)

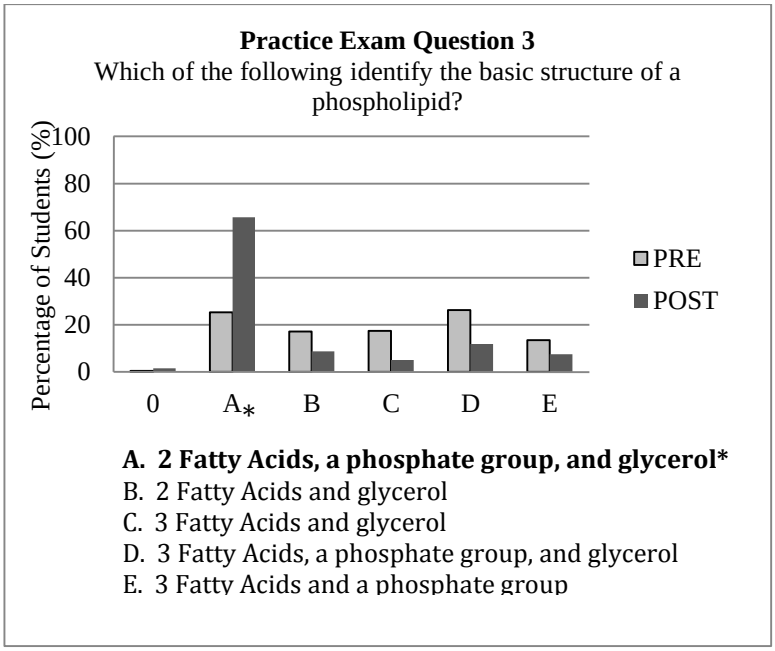


Figure 4.12. Percentage of students' responses to the fall practice pre- and post-instruction exam Question 3.

4.2.2.4. Exam question 4

Question 4 tested students' knowledge on the location in the cell where translation occurs. Proteins are synthesized on the ribosomes that are attached to the rough endoplasmic reticulum (D). Before instruction, 13% of students selected the location of translation (Figure 4.13). Significant gains were made after instruction and 56% of the students identified the correct location of translation (<g>=0.494; p-value<0.001).

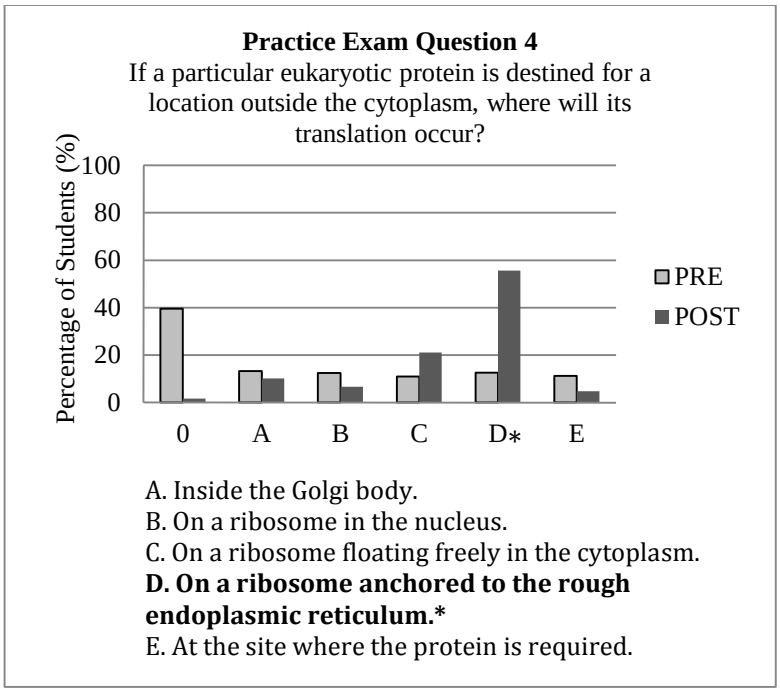


Figure 4.13. Percentage of students' responses to the fall practice pre- and post-instruction exam Question 4.

4.2.3. How did exam performances correlate with students' majors, SAT scores, and BIO100 grade?

Two-sample t-tests were used to determine if students' declared majors were correlated with their knowledge of cells, based on the exam questions (Q1-4) (Table 4.4). The two academic groups were students whose majors required BIO100 and the students whose majors did not, but they took BIO100 to satisfy a general education requirement.

The null hypothesis stated the pre-instruction exam scores for both academic groups were equal, with a confidence interval of $\alpha=0.05$. The null hypothesis is accepted for the 2009 pre-instruction exam scores, indicating the pre-instruction exam scores are not significantly higher with students in majors that required BIO100 ($p<0.05$).

The second t-test compared the gains made by each academic group. The null hypothesis indicated the normalized gain means for each academic group were equal. The null hypothesis is accepted for the 2009 normalized gains, indicating that students in the two academic groups did not have significantly different gains.

Table 4.4. A two-sample t-test suggests students' majors had no significant difference in pre-instruction exam scores or gains made from pre- to post-instruction (n=235).

MAJOR Requirement	**Pre-instruction exam Score (%)**		**Normalized Gain**	
	BIO100	**General Education**	**BIO100**	**General Education**
MEAN	25.943	21.847	0.519	0.462
SD	21.805	20.537	0.484	0.528
***P*-VALUES**	0.079		0.282	

A Pearson's correlation analysis was performed to determine if there was any correlation between students' SAT scores and 2009 BIO100 grades and students' knowledge of cells measured by the pre-instruction exam scores and normalized gain (Table 4.5). The Pearson's correlation matrix reveals no strong correlation between the students' exam performance and either their SAT scores or their BIO100 grades. The matrix shows a moderate positive correlation between students' BIO100 grades and their pre- to post-instruction exam normalized gains. Due to the small numbers of participants in the surveys and interviews, the results may not be meaningful.

Table 4.5. Pearson's correlation matrix indicates a weak correlation between SAT scores, pre-instruction exam scores, and gains. There was a moderate correlation between the BIO100 grade and exam gains in the fall 2009.

	SAT Math	**SAT Verbal**	**SAT Total**	**BIO100 Grade**
Pre-Instruction Exam Scores	0.075	0.092	0.094	0.134
Normalized Gain	0.099	0.037	0.076	*0.247*

4.2.4. Interview results: Fall 2009

The interview responses were scored according to the cognitive complexity using a rubric based upon the SOLO Taxonomy of Briggs and Collins (1991) to answer the question: To what degree do fall students know cell structures and function and understand cells in the living context? The levels of complexity, from low to high are: Pre-structural, Uni-structural, Multi-structural, and Relational. The interview questions are presented below with bar charts indicating the number of students' responses falling under each level of cognitive complexity of reasoning. Due to the small number of interview participants the results are not reported as percentages (n=10).

4.2.4.1. Interview question 1: Content knowledge

In Question 1 of the interview, nine out of ten students gave a Multi-structural definition of a cell that included at least two factors (i.e., a cell is the smallest, functioning unit of life). One student provided a one-part, Uni-structural definition (i.e., a cell is the basic unit of life) and none of the students gave Pre-structural or Relational responses (Figure 4.14).

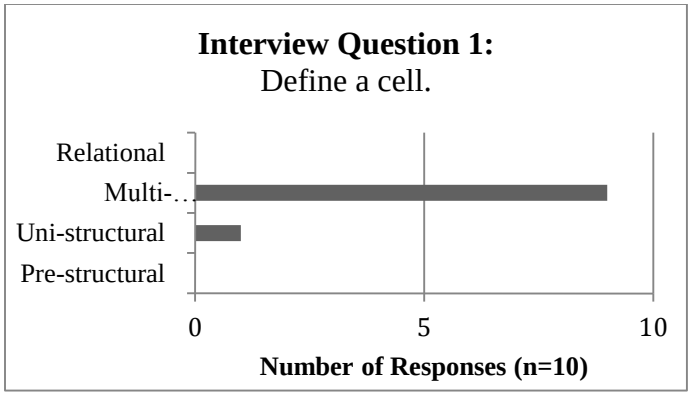


Figure 4.14 Number of students' responses scored by cognitive complexity of reasoning for the interview Question 1.

4.2.4.2. Interview question 2: Content knowledge and contextual understanding

Question 2 of the interview was divided into two parts that assessed students' content knowledge (2A) and contextual understanding (2B) of cells.

Question 2A had three parts that tested students' knowledge of cell structures and functions. First, students were asked to draw a cell. Six out of ten students drew simplistic Uni-structural depictions (i.e., round images of cells). The remaining four students drew Multi-structural images of cells that were irregularly shaped. None of the students drew Pre-structural or Relational images (Figure 4.15).

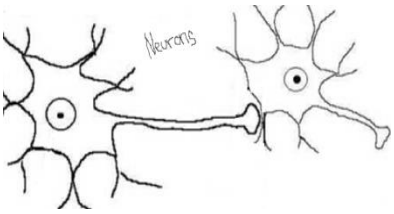
Cell Drawings	
Pre-structural Absent or incorrect No Drawing or drawing of something other than an animal cell.	**Uni-structural** Round, simplistic
Multi-structural Irregular shaped, more complex 	**Relational** Specific animal cell (e.g., neurons) 

Figure 4.15 Examples of students' drawings categorized by the SOLO Taxonomy.

The second part of Question 2A asked students to identify the cell structures in their drawing. No student gave Pre- or Uni-structural responses (i.e., identifying no or one structure), one student answered Multi-structurally (i.e., labeling two or more structures), and nine students had Relational responses and labeled two or more structures with the correct spatial arrangement (i.e., ribosomes on the endoplasmic reticulum).

Lastly, students described the functions of the cell structures. Six out of ten students scored at the Relational level by discussing functions of multiple structures and how their roles play a part in the functioning of the whole cell (i.e., "Cytoskeleton keeps the cell from collapsing in on itself and also provides pathways for the vacuoles to move around I think, it is kind of like a train thing. It is like the lines and it connects everything…things are able to move along the cytoskeleton."). Four students identified at least two functions without relating the functions to the cell (i.e., "the nucleus has the DNA….the lysosome breaks down larger molecules") and were scored at the Multi-structural level. None of the students had Pre- (identifying incorrect function) or Uni-structural (i.e., identifying only one structure's function) responses (Figure 4.16).

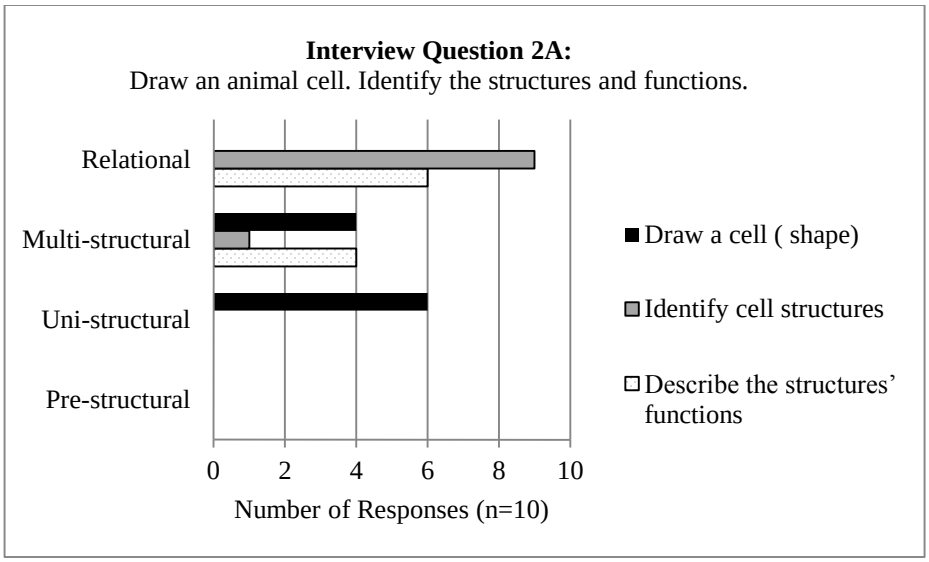


Figure 4.16 Students' responses scored by complexity of reasoning for interview Question 2A.

Question 2B evaluated students' contextual understanding of cells in the body and the use and limitations of cell models. Question 2B was divided into three parts: recognizing the cell model (1), identifying specific cells (2), and describing the movement of cells (3).

First, the students were asked if the cell they drew was a specific or generic cell, and if it was found in the body. Two students believed the generalized cell they drew was a specific cell that was found in the body (Pre-structural). Six students scored at the Uni-structural level and recognized their cell drawing was a generic cell, but thought it was found in the body. Two students stated the cell was generic and not found in the body (Multi-structural). None of the students gave a Relational response and compared and contrasted specific cells to their generic cell drawing.

The second part of Question 2B asked students to identify examples of specific cells (e.g., red blood cell) in a living system (i.e., the human body). The students' responses were spread across the spectrum of cognitive levels. Three students were not able to identify any specific animal cells (Pre-structural). Three students identified one cell example, red blood cells (Uni-structural). Two students discussed several types of cells and scored Multi-structurally. Relational scores were given to two students who compared and contrasted the specific cells.

Students were questioned on the movement of the cell structures for the last part of Question 2B. Two students recognized nutrients and waste are moving in and out of cells (Uni-structural). Five students' responses were Multi-structural, as they discussed how particles and organelles move inside cells (i.e., the vesicles move to transport waste). Three students gave Relational responses, identifying what structures move and the mechanism driving the movement (i.e., "I believe there is something called the cytoplasmic streaming that carries a lot of the chloroplasts around and moves nutrients and anything that needs to be transported so it goes more quickly.") (Figure 4.17).

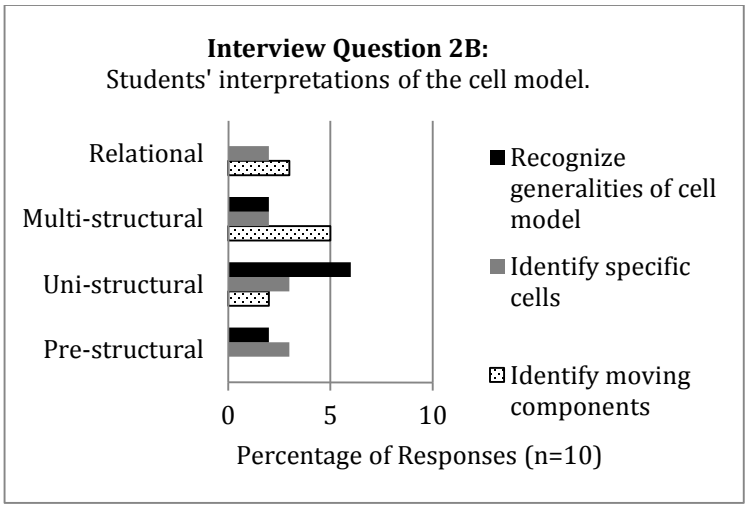


Figure 4.17 Students' responses scored by complexity of reasoning for Question 2B of the interview.

4.2.4.3. Interview question 3: Contextual understanding

The students watched a three-minute animated video clip showing the inner workings of cells within an animal. They then reflected on the video's depiction of cells. The students' feedback was scored based on the cognitive complexity of their response (Figure 4.18). One student focused on identifying cell structures in the video, but did not reflect on the video's impact on her perception of cells (Uni-structural). Four students scored at the Multi-structural level: they identified structures and reflected on the video's usefulness (e.g., "Was it DNA, I think, a while back? Is that like the inner cellular or extra cellular wall or something membrane. Maybe like protein or something going inside of a cell. It seemed like everything was moving like so much I guess. I don't know I guess I never really thought of it moving like that, as like, we do. But no, it just seemed like everything was constantly going and so many different things moving all in one. Umm, their seemed to be a lot of different structures all working together. Like a lot of the tubes or whatever and a lot of things like engulfing other things and producing, like, a new, I don't know whatever they were producing."). A video response was deemed to be

Relational if the student compared and contrasted multiple variables; for example, the purpose and limitations of the animated model would be compared to other cell models (i.e., textbook images). Five responses were scored Relational (e.g., “I notice the video, totally, it showed all the organelles and their functions; how they would work. Obviously, we can't see it actually to the naked eye, but that representation was just a lot more, I guess, practical, you could say. It showed the way they function better so than, like a textbook illustration. It can describe what it is and what it does, but you don’t actually see it in action. Whereas this video, it shows those organelles working, and what's happening. I think, to actually see these things happen, it makes you kind of think more, introspectfully [sic], there's a lot going on in a cell, as opposed to just seeing that on a paper. I know it exists, but what is it really doing? It's kind of a whole other universe. It's a hard concept to try to think about and keep a realistic sense of what's actually happening. I was surprised by the video. It was interesting.”).

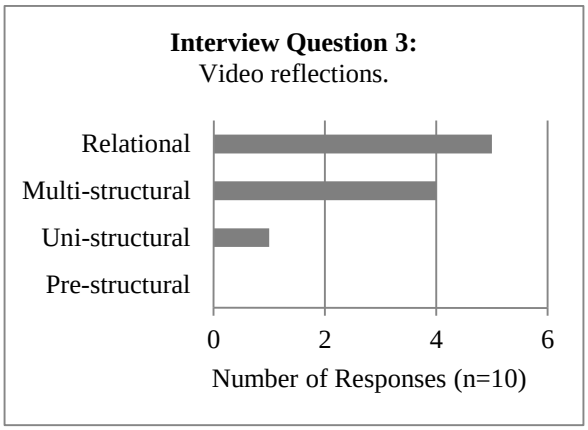


Figure 4.18. Students’ responses scored by complexity of reasoning for interview Question 3.

4.2.4.4. Interview question 4: Contextual understanding

Question 4 was scored in two parts; first, the question examined students' abilities to rank the size of cells to the size of other objects (i.e., hydrogen atom, protein, bacterium, and grain of sand), and second, the students' awareness of a broad range of cell sizes was assessed (Figure 4.19).

Seven out of ten students correctly ranked the sizes of a grain of sand, animal cell, bacterium, protein, and hydrogen atom and scored at the Multi-structural level. The common strategy was to recall what each item was composed of (e.g., "Proteins are smaller because they're inside the cell so it doesn't seem likely they would be bigger because it wouldn't be able to fit in the cell."). Two out of ten students scored Relationally; they noted that the ranking was dependent on the type of animal cell (e.g., "I'm going to say cells are less than a grain of sand, some cells are I guess… if we got like a muscle, because they're so long, it would be bigger than a grain of sand, but I think you could go both ways."). Only one student ranked the objects in the incorrect order by stating a hydrogen atom is larger than a protein.

When the students were asked to compare the size of a grain of sand to an animal cell, five of the ten students indicated a grain of sand is larger than a cell because they could see the grain of sand with their naked eye (Uni-structural). The results indicate students believed all cells are microscopic. After instruction, students were unaware of the variation in cell size; for example, when asked if there are any cells they can see with the naked eye, the student said, "I don't believe so. I'm pretty sure you need a microscope to see them." Only two responses were scored at the Relational level because they indicated they were aware of the variability of cell size by giving examples of cells found

in the body, like a skeletal muscle cell, or an egg, which both could be larger than a grain of sand.

The student that had previously taken anatomy found ranking the size of the grain of sand, animal cell, and bacterium difficult. “I think it is hard to compare to one specific…like, you try to compare a general animal cell or plant cell to a specific thing because they are all different sizes; all different types of tissues, all that. Depending on which individual type of cell you are talking about, and type of bacterium [the ranking could vary].”

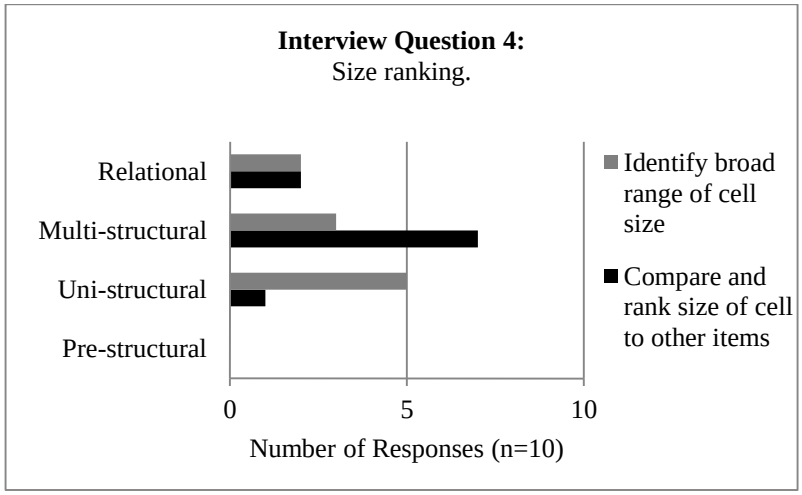


Figure 4.19. Students’ responses for Question 4 of the interview scored by complexity of reasoning.

4.2.4.5. Interview question 5: Contextual understanding

Question 5 investigated students’ beliefs about our global knowledge of cells and current research. The students’ responses were scored on their ability to recognize the importance or cell research and discuss examples of current research (Figure 4.20).

Approximately half of the students interviewed identified characteristics of cells that need further investigation (e.g., “The function of centrioles is unknown.”). The other half of the students were not able to identify any specific research needs; although they indicated an overall appreciation for science research (“There's just things being discovered every day. Yeah, like, I mean, we all always thought there was only, like, how many planets, nine? And there's, like, two more beyond Pluto. Like, I know my biology teacher was, like, yeah, there's, not the one I have now, not my professor, my teacher back from high school was, like, yeah, there's, you know, there's some things that even we still don't know about. I mean, it's totally possible.”). Examples of current research were not given.

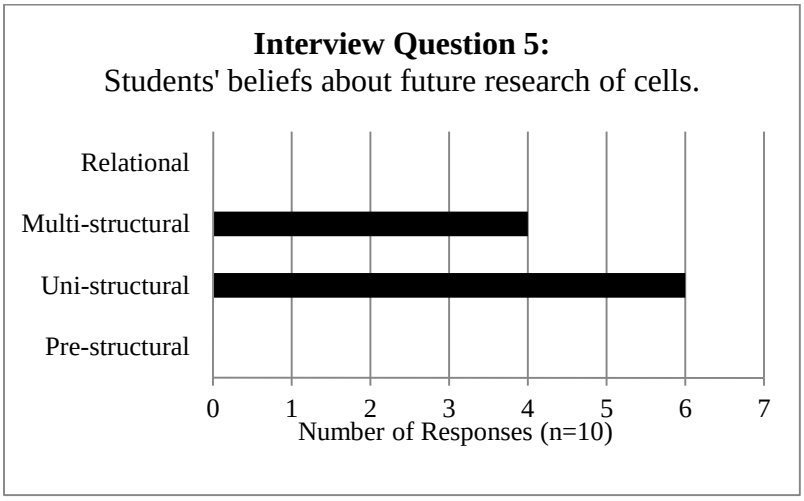


Figure 4.20 Students’ responses for Question 5 of the interview scored by complexity of reasoning.

4.2.5. How did students' cell content knowledge correlate to SAT scores and BIO100 grades?

A correlation matrix was created to analyze the correlation between students' exams scores, pre- to post-instruction practice exam gains, SAT scores, and BIO100 grades (Table 4.6). The correlation matrix contains the Pearson's correlation coefficient, ρ, which indicates the degree of association between two variables that can range from +1 to -1. Students' gains in content knowledge highly correlated with their post-instruction exam scores and SAT scores. The students that gained content knowledge after taking BIO100 did not have a high level of conceptual understanding.

Table 4.6 Pearson's correlation matrix. This suggests a strong correlation between fall students' content knowledge of cells (post-instruction exam scores) and their SAT scores and BIO100 grades, but a weak correlation between their gains and their BIO100 grades (n=10). The bolded values indicate strong and italicized indicate medium correlation.

	SAT math	**SAT verbal**	**BIO100 grade**
Post-instruction exam scores (content knowledge)	**0.586**	**0.554**	**0.607**
Exam content knowledge <g>	**0.540**	**0.523**	*0.490*

4.3. Results summary

In summary, key results for the summer 2009 course, indicated by the exam scores and pre- to post-instruction surveys, include:

1. The exam results indicated after instruction, 80% or more of the summer students correctly identified the definition and function of a cell, mitochondria, chloroplast, and cell membrane, and recognized structures of prokaryotic cells and that surface area is a limiting factor of cell size. While 50% or more of the students selected the

incorrect answers on questions relating to proteins (i.e., carrier proteins, free ribosomes, and integral membrane proteins).

2. The survey results indicated a large portion of students' contextual understanding was low before and after instruction (e.g., 75% of students on the pre- and post-instruction surveys on Question 2B scored at the Pre- and Uni-structural level) when reasoning about characteristics of cells in the context of living organisms (i.e., cell size variability and limitations, commonalities, differentiation, and type). After instruction, students identified significantly more cell structures.
3. Students' BIO100 exams scores had a weak correlate with their SAT scores and a strong correlation with their BIO100 grades.

The fall results are based on the pre- and post-instruction practice exams and interviews. Key results for the fall, though not directly comparable to the summer, are similar and include:

1. Students made significant gains in specific content knowledge as assessed by the BIO100 exams. After instruction at least 60% of the fall students selected the correct answers that assessed their knowledge of characteristics of life, structures in both prokaryotic and eukaryotic cells, structural components of a phospholipid, and the location of translation. After instruction, the interviews indicated students were able to correctly identify numerous cell structures and the moving components of cells.

2. Almost half (44%) of introductory biology students had Pre- or Uni-structural perception about how real cells vary in shape, size, and motility. The interviews indicated that after instruction students had minimal awareness of the purpose and limitations of traditional textbook cell diagrams and several students held alternative concepts based on the generic cell model.
3. Students' exam scores and normalized exam gains did not correlate with their SAT scores, but were weakly correlated to their BIO100 grades.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

This was an exploratory study that investigated three aspects of what basic biology students at the University of Maine understand about cells: (1) students' understanding of cells in the context of the living organism, (2) students' gains in knowledge about cells after completing the one-semester course (BIO100), and (3) comparison of students' final exam scores with their SAT scores and BIO100 grades. The following discoveries are based on results from two semesters, the 2009 summer and fall BIO100 classes. In this chapter I will discuss my three major findings and their implications for teaching.

5.1. Finding 1: Students enter BIO 100 with inaccurate perceptions about how real cells vary in shape, size, and function

My observations suggest students hold alternate conceptions about what cells of different kinds have in common and how they vary. Cells have common features that enable them to be classified as cells, such as transportation of nutrients and other molecules (i.e., endocytosis), metabolism of glucose (i.e., cellular respiration), and reproduction of genetic information (i.e., mitosis). Cells vary in specialized functions and structures. For example nerve cells (unlike white blood cells) have long axons that carry electrical signals as far as a meter, from the spine to the toes, to allow humans to feel temperature or pain. White blood cells (unlike nerve cells) are able to circulate through the body to detect and destroy pathogens such as viruses.

Students interviewed appeared to hold the following alternate conceptions: 1) there is a generic cell that is typical of most cells, 2) cells within an organism vary in basic cellular processes such as protein synthesis and energy metabolism and in the genetic material they contain, and 3) cells are static bags of discrete parts (rather than a complex, interacting system). The misconceptions may have resulted from the misinterpretation of teaching models that are limited in how they portray the dynamic characteristics of cells. More detailed discussion of each alternate conception follows.

5.1.1. Alternate conception A: There is a generic cell that is representative of most cells.

Students' responses on the surveys and interviews suggest that the classic two-dimensional "cell model" that is used to teach the parts of the cell may limit students' perception of the real variability among cells in structure and function (Marzano, Pickering, and Pollock, 2001; Koba & Tweed, 2009, pg 32). Several aspects of students' responses on the surveys and in interviews support this hypothesis. (1) The image that most students drew of a cell was round, with a smaller nucleus in the center, and freestanding. There was little variation among students' drawings, suggesting that their impression of cells closely fits a generalized model used in many textbooks. (2) Interviews did not elicit from students very deep descriptions of how cells really do vary. For example, when asked if there are any cells that can be seen with the naked eye, a student said, "I don't believe so. I'm pretty sure you need a microscope to see them." There were no follow-up questions to determine the degree of students' understanding of cell size variability. (3) When the students were asked to name examples of different cell types, they were unable to name very many types of cells found in the body (Figure

4.17). Three of the ten students were not able to name a specific cell. Three other students hesitated several seconds before naming a specific cell type (i.e., red blood cell), and only two of those students named more than one example (i.e., neuron or epithelial cell). Finally, (4) In the fall interviews, many of the students were unaware of how much cells vary in size. When the students compared the size of a grain of sand to an animal cell, half of the students were confident that the grain of sand was larger, reasoning that they could see the grain of sand with their naked eye. When asked if any cells can be seen with the naked eye, five out of the ten students interviewed stated that all cells are microscopic and can't be seen without a microscope. The smallest cells that would not be able to be seen without a microscope would be a red blood cell; larger cells are neurons and muscle cells, and the largest cells that are visible to the naked eye are bird eggs (e.g., chicken or ostrich eggs).

The finding that many undergraduate beginning biology students probably do not perceive cells with the kind variability in cell type, structures, and sizes that truly exist – even after instruction – may likely stem from the wide use of generic diagrams often seen in biology textbooks. BIO100 students may not be extracting accurate meaning of cells when using the models presented to them in class. If the model is the sole teaching tool, then a limited perception may be cultivated. A generic model may be useful when introducing knowledge about cell structures, but it doesn't portray how actual cells exist in the human body. High school students are expected to be able to identify the usefulness and limitations of models and develop accurate understanding of the concepts being represented (AAAS, 1993; MDOE, 2007), but these teaching standards are not

being met if BIO100 students fail to learn how cells truly vary in structure and function in living organisms and the limitations of the models used for instruction.

Observations here are consistent with other published studies. The AAAS Project 2061 mentions that students believe real cells are just like the textbook model, only smaller (AAAS, 2007). Students in my study did not acknowledge limitations of a model of a typical cell, and how models differ from reality; this has also been seen with students' perceptions of other abstract objects, such as viruses (Jones et al., 2003). Tretter et al. (2006) suggest that students use prototypes to conceptualize scale and define size categories. The size categories varied between elementary, middle, and high school students, but were generally divided into the following categories: *Big* (i.e., planets), *Field Size* (a soccer field), *Room Size*, *Size of Oneself*, and *Small* (i.e., textbook). High school students further divided the *Small* category into *Very Small* (i.e grain of rice) and *Microscopic* (i.e., atoms). Abstract objects that are unable to be view directly had more size variation within their categories; for example, in the *Big* category students lumped planetary and continental distances together. The use of prototypes to perceive scale leads to overgeneralizations; an object, such as an ostrich egg that does not fit the prototypical, *Microscopic* cell category, gets excluded.

5.1.2. Alternate conception B: Cells within an organism vary in basic cellular processes and genetic material.

While cells within an organism vary in size, shape, and function, they all carry out the same basic cellular processes (such as cellular respiration and protein synthesis) and contain the same genetic material. Responses to the summer surveys suggested that students held two misconceptions about universal cell processes and genetic material.

(1) Instead of knowing that all cells perform basic cellular processes to survive, students appeared to believe that cells specialize in processes like protein synthesis and cellular respiration (Summer survey question 2B). The students were given a true or false statement about cell specialization versus essential cellular processes. In the pre-survey, 8 out of 15 students surveyed had a low understanding of cell specialization, they knew cells specialized, but thought that specializing applied to basic cellular processes that all cells must undergo. In the post-instruction survey, several students had a more accurate understanding of cell specialization and correctly recognized that all cells perform protein synthesis and energy production. This observation supports Dreyfus and Jungwirth's (1989) finding that biology students have misconceptions about the commonalities of living cells.

(2) Instead of knowing that all cells within an organism have the same genetic material, 47% of the summer BIO 100 students indicated that genetic information differs among cells within an individual (Summer survey question 2C). Almost half of the students did not distinguish between the role of cell differentiation and genetic information: the concept that all cells within an organism have the same genetic material, but cells use specific parts of the DNA to specialize in bodily function (i.e., producing digestive enzymes). This observation is consistent with that of Dreyfus and Jungwirth (1989) who used the same true/false statement to investigate high school students' understanding of the difference between cellular differentiation and common genetic information.

Although some of my observations are consistent with findings from other studies, the design of my study had some limitations. The Likert type agree-disagree statements used on the survey provided insight into students' misconceptions, but the type of question did not allow for any insights into students' thinking. A more effective strategy for identifying students' deeper grasp of cell commonalities and differences would have been to ask students to compare and contrast different types of cells.

5.1.3. Alternate conception C: Cells are static bags of discrete parts rather than a complex, interacting system.

Most students in the fall interviews were aware of movement of nutrients, waste, and organelles within cells, likely because prior to the interview, the students participated in a laboratory where they used their microscopes to view cytoplasmic streaming in plant cells. But when they watched an animated video of the inner workings of a cell, they were surprised about how active the cellular components were (i.e., vacuoles moving, proteins being synthesized).

When the students watched and reflected on a three-minute cell video titled, *The Inner Life of a Cell* (Bolinsky, Astrachan, and Liebler, 2006), they were impressed by the video's depiction of spatial depth and movement within and among cells. The animated cellular processes helped them visualize a factory-like environment that is in constant and coordinated motion. A student said the video "showed the way they [the cells] function better than… a textbook [does]. There's a lot going on in a cell as opposed to just seeing that on paper." Another student stated "everything was moving so much….[I] never thought of it as moving like that….everything is constantly going." The students' reactions imply that video animation may help students grasp the lively and complex

nature of cells' inner workings, and are consistent with earlier findings that use of animations can increase understanding and retention of cell biology concepts (McClean et al., 2005; O'Day, 2006).

Several students tried to reconcile the video with the textbook image they were familiar with. One student said, "it's harder to pick things out because what I know of what a cell is is what's drawn in the textbooks, so seeing this is a lot different." Another stated, "the pictures [in the video] were … different than I am used to seeing, like the cartoons in books….so the actual 3D models kind of threw me off a little bit. Everything in the [textbook] pictures always look so perfectly rounded but in the 3D model it didn't look very round at all."

Published research supports the idea that textbook models limit students' ideas of the dynamic nature of cells. Koppal and Caldwell (2004) state that the limitations of textbook diagrams are all too often portray cells as a "static bag of parts." They fail to portray scale, context, and complexity, all which result in students' misconceptions (Jones et al., 2003). Published studies suggest that students think models are physical copies of reality and are distracted by the concrete attributes of the model (Adams and Griffard, 2001; Brook et al., 1983; Grosslight et al., 1991). Students may misinterpret abstract representations in all disciplines, for example undergraduate physics and virology students were found to misinterpret compelling visual attributes in velocity versus time graphs and models of viruses, respectively (Clark and Mathis, 2000; Eilam and Gilbert, 2014; Elby, 2000; Jones et al., 2003).

Research indicates that science students and novice teachers have greater difficulty perceiving smaller scales than larger scales (Jones et al., 2008). Yet perception

of scale can be improved with explicit teaching tools (i.e., the film *Powers of Ten*) that visually relate scales and dimensions (Jones et al., 2003 and 2008). Animated videos can be used to convey science concepts ranging in scale from minute to colossal. Computer models can be effective to help students think critically about science ideas and real life settings (Jones et al., 2003 and 2008, Songer, 2007, p. 283). Growing evidence supports the claim that animations are more easily perceived by students and effective when learning about dynamic events (Nicholls and Merkel, 1996; Pollock et al., 2002; O'Day, 2006, Tversky and Morrison, 2002). The role of teachers in helping students interpret visual diagrams, overcome previous misconceptions to assimilate new ideas, and direct their attention to the concept of dynamic cells rather than simple identification may also be important (Mayer and Anderson, 1992; Sweller, 1994; Lowe, 2003).

5.2. Finding 2: During the semester students improved their content knowledge of cells, but not their understanding of cells in a living context.

As a reminder, during two consecutive semesters (summer and fall) BIO100 students were assessed in their content knowledge of cells (by way of the course pretest and final exam) and in their contextual understanding of cells at the beginning and end of each semester (by way of interviews and a written survey). Results of the surveys, interviews, and course tests were compared to see how students' knowledge and understanding of cells changed during the semester. Although in retrospect, comparison among three different assessment modes yields limited hard evidence, observations were interesting and instructive.

5.2.1. Students gained in their content knowledge during the semester

Students in both summer and fall semesters did significantly better on questions about cell structures at the end of the course than at the beginning of the course. The summer students identified significantly (p-value <0.001) more cell structures in their cell drawings at the end of the semester, and the fall students made significant gains on the exam questions that were about cell structures. These results suggest that the pedagogy used in BIO 100, textbook-supported lecture and assessments in combination with inquiry-based laboratories, does result in gains in factual knowledge about cells.

5.2.2. Students' perception of the variability among cells in a living context did not improve during the semester

Question 2 of the summer survey asked students to explain whether they agreed or disagreed with four statements that were based on alternative conceptions of cells (Dreyfus and Jungwirth, 1989). The four statements assessed students' understanding of cell size (A), cell commonalities (B), cell differentiation (C), and cell classification (D) (Figure 4.4). For each of the four statements, approximately 75% of the students (total participants, n=15) gave a Pre- or Uni-structural response on both the pre-survey and the post-instruction survey, indicating little overall change in the cognitive level of their response (Figure 4.5).

These four concepts are relational ideas that are based on how cells relate to their surroundings; they are facts that are not meant to be memorized. In a traditional lecture-based classroom setting the alternative conceptions (such as the idea that most cells look like the generic composite often used in textbooks) will likely persist because they are not explicitly challenged (NRC, 2005). The lack of minimal improvement with students'

understanding supports Koba and Tweed's (2009, p. xii) claim that biology classroom lessons and assessments typically focus on the lower level of Bloom's Taxonomy (i.e., lists of vocabulary, labels, and steps in processes), which extrinsically motivate students to focus on details rather than concepts.

5.3. Finding 3: Students' exam scores that assessed content knowledge and their SAT scores were not correlated.

The weak correlation between scores on exam questions and SAT scores, could be because of two factors: 1) the exam questions were testing factual knowledge versus academic reasoning, and 2) the sample size was small.

While this study has major flaws in the methods of comparison, it is evident that the BIO100 examinations were knowledge-based and the literature supports the claim that there are negative repercussions when science courses focus on factual-based memorization. Of the twenty BIO100 exam questions that pertained to cells (Table D.1), all of them required low cognitive-level thinking, such as recalling terminology, classifying information, re-stating theories, and identifying structures related to cells. The exam questions did not require any level of synthesis based on Bloom's taxonomy (Bloom, 1956). Students' performance on each question depended upon their factual knowledge of the specific topic, rather than their ability to synthesize information to support a line of reasoning. For example, the following is a 2009 summer term exam question that assessed students' factual knowledge of the function of the endoplasmic reticulum:

Which structure is the site of the synthesis of proteins that may be exported from the cell?

A. rough ER
B. lysosomes
C. peroxisome
D. Golgi vesicles
E. Nucleus

Past studies claim that biology undergraduate courses often emphasize fragmented, fact-based assessment questions (AAAS, 1989; Bransford et al., 1999; Momsen et al., 2010; Zheng et al., 2008). Most classroom exams, standardized tests, and published textbook tests assess domain-specific knowledge and emphasize only low-level reasoning such as recalling and recognition tasks (Bol & Strage, 1996; Crooks, 1988; Fleming & Chambers, 1983; Haertel, 1986; Madaus, Maxwell West, Harmon, Lomax, & Viator, 1992).

Biology students are typically assessed by their ability to memorize science vocabulary, rather than understanding science concepts and their application (Gallagher, 1991). It can be easy to misperceive an exam question that involves memorization of complicated terminology, such as "What is the chemical pathway for the Krebs Cycle?" as challenging students' ability to synthesize and reason, when it may simply indicate ability to memorize (or time spent memorizing). An alternative question such as, "Explain how your food is metabolized so cells are able to utilize the energy" would do a better job of assessing students' ability to synthesize information to give a reasoned response.

5.4. Conclusions and suggestions for future research

This study sheds light on how undergraduate students perceive cells. Two major issues limit application of the findings to a wider population: (1) the number of participants surveyed (summer n=15) and interviewed (fall n=10) was small compared to the number of students taking BIO 100 (summer BIO100 n= 40; fall BIO100 n= 483) and (2) the research tools used in the two different semesters were misaligned in that they assessed students' content knowledge and conceptual understanding using different methods in different combinations (interviews, written surveys, and pre-test and final exam scores).

Fewer students volunteered to participate in the summer surveys (n=15) and the fall interviews (n=10) than I hoped for. To attract more volunteers for future studies, I suggest offering incentives (i.e., participation grade or bonus points) to ensure a statistically meaningful sample size.

The research tools (i.e., surveys, interviews, and exams) varied between the two semesters, and the concepts assessed were not aligned between the exams and surveys. The surveys and interview questions were created to document students' perceptions of cells, but the exam questions were pre-determined questions implemented as part of the BIO 100 course. I suggest revising the written survey and exam questions to better match, so direct comparisons can be made. See Table E.1. in Appendix E for suggestions for revised questions that could be used on surveys and exams to assess students' conceptual understanding of cells.

5.5. Summary and implications for teaching

The goal of this exploratory study was to find out what students entering and completing a college basic biology course understand about cells in terms of (1) cells in the context of living organisms, (2) their gains in knowledge about cells after completing the one-semester course (BIO100), and (3) comparison of students' final exam scores with their SAT scores and BIO100 grades. The findings are: (1) at the beginning of the course BIO100 students have alternate conceptions about how cells exist in a living context, (2) those alternate conceptions persist through the course, although students gain in knowledge of factual content about cells improves, and (3) students' factual knowledge about cells (exam scores) do not have a strong correlation with their SAT scores.

5.5.1. Implications for Finding 1: Strategies for deepening students' perception of variation among living cells

One cannot imagine how students can fully understand critical biological processes that govern their own physical health without having accurate perception of cells and how they function in our bodies. However, teaching about cells can be challenging, and misconceptions may arise due to the microscopic scale of most cells and the complexity of their molecular functions. Two-dimensional picture models have long played a key role in helping students visualize microscopic cells macroscopically, and only in recent years has technology begun to provide many new online tools for visualizing cells in realistic ways that are widely accessible and affordable or free (McGill, 2008).

Dynamic web-based models can help students visualize the dynamic nature of cells. The students should gain a richer appreciation of cell complexities and variation by analyzing multiple cellular representations; i.e., the traditional textbook model, animated videos (e.g., *The Inner Life of a Cell*), and direct examination of cytology slides. Animated videos, such as Harvard and XVIVO videos: *The Inner Life of a Cell, Powering the Cell: Mitochondria,* and *Making the Complex Simple,* visualize how fluid and complex cellular environments are. With the combination of diverse animations, teachers can convey dynamic cell processes and stimulate a conversation with students about how the videos changed their perception of cells (Smith, 2004; McClean, 2005; O'Day, 2006; Bolinsky, Astrachan, and Liebler, 2006).

Students are expected to extract accurate information from models, but if students are unable to do so, lessons should try to explicitly target common misinterpretations of models made by students. Students exposed to a variety of cell models (i.e., animations and textbook diagrams) might be asked to identify the model's purpose and limitations (Richmond *et al.,* 2010). They can discuss the usefulness and confines of the traditional textbook cell models and compare those models to cells they see under the microscope and in videos.

To increase contextual understanding of how much cells vary, students might observe a variety of cells (i.e., swab of cheek cells, a chicken egg, and a blood smear) and ask them to compare and contrast each cell type (Marzano, Pickering, and Pollock, 2001). Students can rank their cells by size and rank to other objects (i.e., a grain of rice, sand, or a penny) to get a better appreciation of diversity in scale.

Biology curriculum should broaden students' awareness of diversity in specific cell types and their similarities in cell processes (e.g., protein synthesis and DNA) and differences in cell functions (e.g., transport oxygen, contract to exert force). Lazarowitz and Naim (2012) found that 9th-grade students performed better on the exam and gained a better appreciation for cell structures and functions after creating their own three-dimensional cell model. Students could extend the activity by making several models of specific types of animal cells (i.e., neuron, myocyte, and red blood cell) and reflecting on the similarities and differences between the cell types. Saunders and Taylor (2014) suggest using an online database called "The Cell: An Image Library" (http://www.cellimagelibrary.org/) to improve students' understanding of the diversity of cell types and how their variable structures relate to their specific functions. With the use of multiple cell representations students might gain a deeper contextual understanding of cell types, which has been suggested in other science and math disciplines (Ainsworth, 1999; Ainsworth, et al., 2002).

5.5.2. Implications for Finding 2: Shift some of the focus from factual knowledge to contextual understanding

One of the primary teaching implications of the present study is to emphasize the value of learning concepts about cells and reasoning (i.e., cells are complex and dynamic; cells have commonalities and variability in size, shape, and function) rather than memorizing vocabulary (i.e., identifying organelles and their functions) (Perry, 1970; King and Kitchener, 2004).

It has been shown that if teachers provide explicit learning goals that shift the focus from facts to concepts then there is an increase students' academic achievement (Koba & Tweed, 2009; Marzano, Pickering, and Pollock, 2001). For example, rather than requiring students to memorize cell structures, ask them to relate how those structures contribute to the cell to allow the cell to function in the tissue and within the organism, to elicit a deeper level of thinking.

5.5.3. Implications for Finding 3: Assessments should measure students' degree of understanding as well as content knowledge

Observations made here support the hypothesis that assessments requiring knowledge-based recall of facts and terminology about cells do not necessarily assess academic ability and higher order thinking (as indicated in this study by the SAT scores). Future biology curricula and assessments should align to promote higher-order thinking about cells.

Aligning learning, pedagogy, and assessments to a higher-order thinking will result in students who have a deeper understanding of biological principles. To assess the efficacy of lessons about cells, it may be strategic to use assessments that align with the course objectives in content knowledge and cognitive demand, such as synthesis and application.

5.6. Conclusion

Limiting imagery of cells in the classroom to just one or a few generalized models and reducing the lessons to memorizing details may limit students' perceptions and restrict students' appreciation of the complexity and awe-inspiring capabilities of cells. Cells allow us as individuals to live, function, and interact with other organisms in whole ecosystems in a complex and interdependent web of life. Teachers and students alike will be able to appreciate the exciting and dynamic nature of cells with the use of technology and guidelines from this and other educational studies.

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APPENDIX A

BIO100 CELL OBJECTIVES (2009)

Cells 1 and 2 Campbell & Reece, Chapter 6

Overall Objectives:

- You will be introduced to the cells in each of the three Domains of life.

- Prokaryotic cells are either those of Bacteria or Archaea. What is the difference between these two classes of cells?

- Eukaryotic cells are varied. We will look at typical plant and animal cells. What are the distinguishing features between these two types of cells?

- You should become familiar with the basic activities of cells and how they hold together.

Concepts from Chapter 6:

Concept 1- Cells are the basic unit of life: they are complex and are able to do a great variety of things.

1. What are some of the things that all or most cells are able to do?

2. What are some of the specific structures that define a cell?

Concept 2 - We use a variety of types of microscopes to visualize and study cells.

1. What are two types of light microscopes that you use in lab, and what level of cellular detail is each able to resolve?

2. What are two types of electron microscopes? What types of things within or on a cell do they allow you to see that you cannot see with your own lab microscopes?

3. If you were trying to study the structure of the mitochondria within a cell, which type of microscope would you use? If you were trying to study the mating behavior of fruit flies, what type of microscope would you use? If you wanted to see the shapes of individual pollen grains, what type of microscope would you use?

4. What is another way to study cells that does not involve microscopes? What sorts of things can you find out about using this method?

Concept 3 - The cells of prokaryotic organisms differ in significant ways from cells of eukaryotic organisms.

1. We can talk about two main kinds of cells that are dramatically different from each other: those of prokaryotes and those of eukaryotes. So, first, what organisms are we talking about when we say prokaryotes, and what organisms are we talking about when we say eukaryotes? Are humans prokaryotes or eukaryotes? What about corn plants? Ferns? Pine trees? *E. coli*? Salmonella? Amoebae? Mushrooms?

2. What properties are the same in both prokaryotic and eukaryotic cells?

3. What properties distinguish a prokaryotic cell from a eukaryotic cell?

4. How are phospholipids arranged in a biological membrane?

5. Do all cells (prokaryotic and eukaryotic) have cell membranes? Cytoplasm? A nucleus? Mitochondria? Ribosomes? DNA? One or more chromosomes?

Concept 4 – Prokaryotic cells are small, but they carry out complex functions and they are extremely numerous. The prokaryotic cells we are most familiar with are the bacteria.

1. Does a prokaryotic cell have a nucleus? Does it have a chromosome?

2. What is the genetic material of a prokaryotic cell?

3. What surrounds a bacterial cell? Does it have a cell membrane? Is there anything outside of the cell membrane?

Concept 5 – Eukaryotic cells are larger than prokaryotic cells, though most are still quite small. The two major types of eukaryotic cells we are familiar with are animal cells and plant cells.

1. What distinguishes an animal cell from a plant cell? 2. What structures are common to both animal cells and plant cells?

Concept 6 – Cells must be small - they must have a small surface-to-volume ratio so that nutrients and other molecules entering the cell at the cell surface can diffuse to other parts of the cell quickly without wasting energy.

1. As a cell increases in size, does its volume increase at the same rate as its surface area? If not, why not?

2. Can you think of a way a cell might increase its size without increasing the distance a nutrient molecule would have to diffuse to get from the outside to mitochondria on the inside?

3. About how large do the human cells in your body get? Can you see them using your dissecting microscope? Your compound microscope?

4. An amoeba is a single celled organism you may be familiar with. It can be 740 μm in length, about 100 X larger than the width of a human red blood cell! How do you it could not exist if it were in the shape of a cube? Why or why not?

Concept 7 – Eukaryotic cells contain a number of different membrane bound organelles that have specific functions.

1. What are some of the organelles found in a eukaryotic cell?

2. What are the general functions of each of the following organelles: nucleus, mitochondria, lysosomes, endoplasmic reticulum, Golgi apparatus, peroxisomes, vacuoles?

Concept 8 – Mitochondria and chloroplasts differ from other organelles, and these differences have led scientists to propose that they were both derived from bacteria and became incorporated into eukaryotic cells. This is called the endosymbiotic theory of mitochondrial and chloroplast origins.

1. What are some of the characteristics of both chloroplasts and mitochondria that led to the endosymbiotic theory or their origin?

2. What are some characteristics that distinguish a mitochondrion from a chloroplast?

3. In general, what is the function of mitochondria? Of chloroplasts?

4. Are mitochondria found in animal cells? In plant cells?

5. Are chloroplasts found in animal cells? In plant cells?

Concept 9 – Cells have a shape that is maintained by an internal scaffolding— their cytoskeleton. The cytoskeleton is also involved in cell movement.

1. What components make up the cytoskeleton of a cell?

2. What do microtubules do in a cell? Can they be used to traffic things around within the cell? If so, how? What are two specific instances of this, as shown at the end of the Lecture Movie?

A Walk Through Some of the Organelles Found in Eukaryotic Cells The nucleus houses the genetic material and controls what gets in and out using its nuclear pores.

1. What are some of the characteristics of the nuclear membrane?

2. How would you describe a nuclear pore?

3. What is the nuclear lamina, where is it, and what is it used for?

4. The nuclear membrane is continuous with what organelle outside of the nucleus? Why do you think the nuclear membrane is continuous with this organelle?

5. What is the nucleolus?

The endoplasmic reticulum is an extensive series of membrane bound channels in which a number of different types of molecules are processed. There are two different types of endoplasmic reticulum, rough and smooth.

1. What are the differences between rough and smooth endoplasmic reticulum?

2. List some of the specific functions of smooth endoplasmic reticulum.

3. List some of the specific functions of rough endoplasmic reticulum.

The Golgi is an extensive series of membrane stacks. Vesicles from the ER attach to the Golgi (*cis* side) and deposit proteins. Proteins leave from the opposite side (*trans* side) for their final destinations. While proteins move from the *cis* to the *trans* side, they are modified.

1. List some of the main functions of enzymes within the Golgi?

2. List the main role of the Golgi.

Lysosomes are bags of enzymes that degrade macromolecules and defective old organelles for recycling.

1. What is the pH within a lysosome? At what pH do lysosomal enzymes work best?

2. What is the pH of the cytoplasm? Do lysosomal enzymes function at this pH? 3. What are some good reasons for a cell to have lysosomes? What are some good reasons for having lysosomal enzymes that work at a different pH than the pH of the cytoplasm?

Vacuoles are used to sequester things: food vacuoles, contractile vacuoles, and central vacuoles all sequester different things.

1. Where can each of these different types of vacuoles be found: food vacuoles, contractile vacuoles, central vacuoles?

2. How can each of these different types of vacuoles be used: food vacuoles, contractile vacuoles, central vacuoles?

The endomembrane system is a series of membrane bound organelles that are connected either by direct connection or by vesicles blebbing off of one and fusing with another.

1. Is the endomembrane system found in eukaryotic cells, prokaryotic cells, or both?

2. What are organelles are included in the endomembrane system?

3. There must be some advantages to having an endomembrane system. What advantages you can think of?

APPENDIX B

INSTITUTIONAL REVIEW BOARD (IRB) APPROVAL FORM

MAY/20/2009/WED 01:19 PM CLIMATE CHANGE INSTI FAX No. 2075811203 P. 001/001

UNIVERSITY OF MAINE – APPLICATION FOR APPROVAL OF RESEARCH WITH HUMAN SUBJECTS
(See instructions on reverse for completing application)

PRINCIPAL INVESTIGATOR: Melissa Lewis email: melissa.a.lewis@umit.maine.edu
CO-INVESTIGATOR(S): _____
FACULTY SPONSOR (if any): Molly Schauffler, PhD.
TITLE OF PROJECT: Undergraduate Conceptions of Living Cells
PROJECT START DATE: May 2009 **PI DEPARTMENT:** Masters of Science in Teaching
MAILING ADDRESS: 517 South Rd Farmingdale, ME 04047 **TELEPHONE:** 1-207-468-4608
FUNDING AGENCY (if any): _____ **CONTRACT/GRANT #:** _____
STATUS OF PI (circle one):
FACULTY/STAFF/GRADUATE/UNDERGRADUATE/OTHER _____

1. If PI is a student, is this research to be performed:
   ____ for an honors thesis? X for a master's thesis?
   ____ for a doctoral dissertation? ____ for a course project?
   ____ other (specify) _____
2. Does this application modify a previously approved project? N. If yes, please give assigned number (if known) of previously approved project: _____
3. Do you believe this project is exempt from further review requirements? Y (Y/N, unsure). Information regarding exemption categories may be found on pages 4-5 of the Policies and Procedures (http://www.umaine.edu/research/Ethical/humanpolicy.pdf).
4. Is an expedited review requested? Y (Y/N). Information regarding expedited review procedures may be found on pages 8-11 of the Policies and Procedures (http://www.umaine.edu/research/Ethical/humanpolicy.pdf).
5. Has everyone named in this application completed the mandatory training on the Protection of Human Subjects of Research? Y (Y/N). Approval will not be granted until training has been completed. The tutorial is found at www.umaine.edu/irb.

SIGNATURES: All procedures performed under the project will be conducted by individuals qualified and legally entitled to do so. No deviation from the approved protocol will be undertaken without prior approval of the Board.

Faculty Sponsors are responsible for oversight of research conducted by their students. By signing this application page, the Faculty Sponsor ensures that the conduct of such research will be in accordance with the University of Maine's *Policies and Procedures for the Protection of Human Subjects of Research.*

5-20 Melissa A. Lewis-Knapp Molly Schauffler
Date Principal Investigator Faculty Sponsor

_____ _____
Co-Investigator Co-Investigator

****

FOR BOARD USE ONLY Application # 2009-05-20 Date received 5/20/09 Review (F/E): E
ACTION TAKEN:

X Judged Exempt; category 1. Modifications required? Y (Y/N) Accepted (date) 5/29/09
____ Approved as submitted. Date of next review: by _____.
____ Approved pending modifications. Date of next review: by _____.
Modifications accepted (date): _____.
____ Not approved. (See attached statement.)

Date: 5/26/09 Chair's Signature: Cynthia A. Erdley 12/03

Informed Consent Form

You are invited to participate in a research project being conducted by Milissa Lewis, a graduate student in the Masters of Science in Teaching at the University of Maine. The purpose of this research is to investigate students' conceptual understanding of cells and corresponding factors. You must be at least 18 years of age in order for your data to be used in the study.

What Will You Be Asked to Do?

If you decide to participate, you will be asked to:

1. **Allow me access to your Bio 100 Preliminary, Final exam scores, academic major, year in school, and your SAT scores.** The information will be accessed from SYNAPSE, a biology course database, and the Biology Department records. Seth Tyler, a UMaine biology professor and manager of SYNAPSE will gather the desired data into a spreadsheet the my advisor and I will have access to. This will help me interpret the results of my study. Once scores are matched with survey responses, your name will be removed from the data, and it will not be possible to link any individual with any part of the data set or the findings generated by my study.

2. **Possibly participate in a 20-minute interview** to watch a short clip on cells and answer several follow-up questions. Up to 15 interviewees will be chosen randomly from the class. The interviews will take place in Murray Hall and will be voice recorded. Participation is voluntary and, if selected, you may chose at any time to not participate in the interview.

   Here is an example of the kind of question you will be asked in an interview: *Draw and label a cell.*

Although your name will initially be present on the questions, interviews, and exams, your responses will be transcribed and coded for analysis, and to protect your identity, no personal identification (i.e., your name or University identification number) will ever be used in connection with the data.

Risks & Benefits

Except for your time and inconvenience, there are no risks to you from participating in this study. While this study may have minimal direct benefit to you, this research will help us learn how to improve instruction and learning about cells.

Confidentiality

To protect your identity, once your responses have been recorded and coded, your name will be removed entirely from the research database. Original survey responses and interview tapes and the key linking your name to your responses will be kept in the investigator's locked office not beyond December 2010, and then will be destroyed. My faculty advisors will have access to the coded, summarized data. Your name or other identifying information will not be reported in any publications.

Voluntary

Participation is voluntary. If you choose to take part in this study, you may stop at any time during the study. You may skip any questions you do not wish to answer. Whether you participate or not will not affect your grade in this course.

Contact Information

If you have any questions about this study, please contact me at milissa.a.lewis@umit.maine.edu. You may also reach my academic advisor, professor Molly Schauffler in the Bryand Global Sciences Ctr., University of Maine, Orono, ME 04469 at 207-581-2707 (or email molly.schauffler@umit.maine.edu).

If you have any questions about your rights as a research participant, please contact Gayle Jones, Assistant to the University of Maine's Protection of Human Subjects Review Board, at 581-1498 (or email gayle.jones@umit.maine.edu).

Your signature below indicates that you have read and understand the above information. If you desire, approach your instructor for a copy of this form.

Are you 18 years or older? Y/N

Print Name:_____

Sign Name: _____
Date:_____

APPENDIX C

INTERVIEW QUESTIONNAIRE

Interview Questionnaire

1. What is a cell?
    a. *In reference to the building block of life: How would you define life?*
2. Draw a cell, label the structures and functions of the structures.

    a. *What kind of cell did you draw*?
        i. *If they drew a plant cell ask them to draw another type of cell (they will then draw an animal cell).*
        ii. *How did the first and second cell differ?*
    b. *Is this animal cell a specific type of cell or a generic cell?*
    c. Draw as many specific types of animal cells you can think of.
        i. *What are they?*
        ii. *How do they differ from the generic cell drawn above?*
        iii. *Are all same structures present?*
        iv. *Do the structures look the same?*
    d. Draw the cell membrane. Describe the characteristics of the membrane.
        i. *Answer=Semi-permeable:*
            1. *What does this mean?*
            2. *What particles can move in and out?*
            3. *What regulates the movement of 'good' materials in and not 'bad' materials?*
        ii. *Answer=Fluid:*
            1. *Define fluidity.*
                a. *What is fluid about the cell membrane?*
                b. *In your drawing point to the specific structures that are moving, if any. Describe that movement.*
            2. *Can fluid be used to describe any other aspect of the cell? Explain.*
                a. *Are the organelles moving within the cell? Explain.*
                b. *Does the whole cell move in tissue? Explain.*

Figure C.1. Interview questionnaire and script

3. Watch a short video on the inside of a cell.
    a. Take note of anything that: you recognized or surprised you.
        i. Have you seen this video before, if so where and when?
        ii. How does this depiction of the cell compare to models you have seen in the text book? How do the models impact your perception of cells?

4. Look at your original drawing of an animal cell.

        i. Is there anything you would change about your representation of the cell? If so, what?

5. Rank the sizes. In order to understand the size of your cell you have drawn, state whether the following is greater than, equal to, or less than. Explain your reasoning for each.
    a. *What type of cell are they choosing to rank?*
        i. *If they mentioned several types of cells: How do the rankings compare between the varying types of cells?*
    b. *Do you need to use a microscope to see all individual cells?*

    Cell _____ Grain of sand

    Cell _____ Bacterium*

    Cell _____ Hydrogen atom

    Cell _____ Protein

    Now rank the following from smallest to largest: the cell you drew, a bacterium, grain of sand, hydrogen atom, and protein.

    **Note: State to the interviewee what a bacterium is.*

6. State to what extent you agree or disagree with the following statement and explain your reasoning.

				Statement
Strongly Agree	Somewhat Agree	Somewhat Disagree	Strongly Disagree	There still remain cell components with unknown functions that are in need of further research.
Explanation:				

    a. *Why do you think this? In the classroom, do you discuss what aspects of cells need further research?*

Figure C.1. continued.

2. Draw a cell, label the structures and functions of the structures.

a. *What kind of cell did you draw*?
   i. *If a plant cell ask: Draw another type of cell an animal cell).*
   ii. *How did the first and second cell differ?*

b. *Is this animal cell a specific type of cell or a generic cell?*

c. *Draw as many specific types of animal cells you can think of.*
   i. *What are they?*
   ii. *How do they differ from the generic cell drawn above?*
   iii. *Are all the structures present?*
   iv. *Do the structures look the same between the cells?*

d. *Let 's look at one structure more closely, the cell membrane. Describe the characteristics of the membrane.*
   i. *Answer: Semi-permeable:*
      1. *What does this mean?*
         a. *What particles can move in and out?*
         b. *What regulates the movement of 'good' materials in and not 'bad' materials?*
   ii. *Answer: Fluid:*
      1. *Define fluidity.*
         a. *What is fluid about the cell membrane?*
         b. *In your drawing point to the specific structures that are moving, if any. Describe that movement.*
         c. *Can fluid be used to describe any other aspect of the cell? Explain.*
            i. *Are the organelles moving within the cell? Explain.*
            ii. *Does the whole cell move in tissue? Explain.*

Figure C.2. Interview Question 2 assessed contextual understanding (fall semester). The scripted interview protocol questions are italicized.

APPENDIX D

CELL LESSON PLAN & ASSESSMENT

Dynamic living cells	Biology High school
Overview: The lesson conveys the dynamic nature of cells in the living context with emphasis on cells variation in size, shape, motility, and specialization.	**Materials:** • Computer and projector • Whiteboards and markers • Microscopes • Cytology slides (stain, swab, slides, coverslips, oil) • Masking tape • Ruler, meter stick
Objectives: The following Science and Technology from the 2007 MLR will be covered: 1. **A1-Systems:** Describe how individual cell types contribute to the tissue and body 2. **A2-Models:** Evaluate cell models by comparing cytology slide to multi-media animation and textbook diagrams; Understand all models have purposes and limitations 3. **A3-Scale:** Compare sizes of specific cell types to explain how cells function in the living body 4. **E3- Cells:** Describe the similarities and differences in the basic functions of cells in regards to their structures and processes (i.e. protein synthesis, motility); Describe how cells differentiate forming specialized systems that carry out basic life functions	**Other Resources:** http://pharmchem.ucsf.edu/research/physbio/light-microscopy • Visualizing actual cell structures http://www.nytimes.com/2010/11/16/science/16animate.html?_r=0 http://www.xvivo.net/animation/the-inner-life-of-the-cell/ http://ascb.org/bioeducate-k-12-students-and-teachers-resources/ http://multimedia.mcb.harvard.edu/media.html

Figure D.1. Cell lesson based on the study's findings.

Activities:

Introduction: What it means to be a cell (60 minutes):

1. Pretest: See Assessment section
2. Ask the students to define what a cell is.
3. Then have the students draw an animal cell
4. As a class come to a consensus on the definition and compare drawings. Discuss the similarities and differences among drawings. Ask the students where their perception of cells comes from.
5. Lead a discussion and note taking session on what all cells need to survive in regards to structure (i.e. nucleus, cell membrane, mitochondria) and processes (i.e. protein synthesis, DNA replication, energy, waste disposal)

Part I: Cells are abstract, so we use models (45 minutes):

1. Have the students split into groups, with each group having a white board. Have the students make a chart on the whiteboard with three columns for the three diagrams and two rows for pros and cons.
2. Show three representations of cells: cytology of real cells, 2-D textbook diagram, *Inner life of a cell* © XVIVO (Bolinsky, Astrachan, and Liebler, 2006)
3. As you show the models, students should be filling in the pros and cons chart.
4. Lead a discussion about why we need models to look at cells, the pros and cons list (i.e. how they coveys structures, motility, part of a system), and the impact of each model on their perceptions.

Part II: Cells vary in size, shape, and function (90 minutes):

1. Introduce cell differentiation and why its significant.
2. Group work- Name five types of specific cells you find in your body and list their functions and size (length). Use resources to look them up if you need to. Alternative: You can assign students several cells and make sure there are no duplicates. Then the students can report out on their findings.
3. Have the students observe the specific cells under the microscope. Briefly sketch them.
4. Have the students describe how the cells' characteristics relate to their function in the tissue and human body.
5. Have the students compare the cell sizes by creating a larger scale model (1nm=1inch); use masking tape to represent each cell length
6. Facilitate a discussion on cell types and how they vary in size, shape, and function. Ask the students how their first cell drawing from the introduction compares to the specific cell types they saw using the microscope. Emphasize models limitations on scale and variability.

Figure D.1. continued.

Part III: Conclusion: Cells are complex (20 minutes):

1. Show a cell animation video: *Making the Complex Simple* © XVIVO (https://vimeo.com/32267403)
2. Lead a discussion in how cells contribute to the entire human body and the importance of their similarities and differences that allow us to function.

Alternative ending/Extension:

1. Give an example of a cell malfunctioning, have the students predict its effect on the tissue, and how it manifests into a whole body disease (e.g. demyelination of neurons and multiple sclerosis).
2. Research stem cells- define a stem cell, what are their uses in the medical field, describe if there are ethical implications (debate ideas in class)
3. Research cancerous cells- compare a healthy cell with a cancerous cell, what makes cancerous cells devastating to our organs/health, research cancer topics (types, current research breakthroughs, treatments), interview someone you know that has been impacted by cancer, present to class

Assessments:

Pretest:

1. Rank the of size the following items: sand, bacterium, chicken egg, protein, virus, mouse nerve cell, an elephant nerve cell, red blood cell.
2. Name three things cells can have in common and three things that can vary between cell types.
3. Why do we use models in science? What are two aspects you need to know about any model before you use it?

Post-tests: See assessment document (Table E.1).

Figure D.1. continued.

Activities:

Introduction: What it means to be a cell (60 minutes):

6. Pretest: See Assessment section
7. Ask the students to define what a cell is.
8. Then have the students draw an animal cell
9. As a class come to a consensus on the definition and compare drawings. Discuss the similarities and differences among drawings. Ask the students where their perception of cells comes from.
10. Lead a discussion and note taking session on what all cells need to survive in regards to structure (i.e. nucleus, cell membrane, mitochondria) and processes (i.e. protein synthesis, DNA replication, energy, waste disposal)

Part I: Cells are abstract, so we use models (45 minutes):

5. Have the students split into groups, with each group having a white board. Have the students make a chart on the whiteboard with three columns for the three diagrams and two rows for pros and cons.
6. Show three representations of cells: cytology of real cells, 2-D textbook diagram, *Inner life of a cell* © XVIVO (Bolinsky, Astrachan, and Liebler, 2006)
7. As you show the models, students should be filling in the pros and cons chart.
8. Lead a discussion about why we need models to look at cells, the pros and cons list (i.e. how they coveys structures, motility, part of a system), and the impact of each model on their perceptions.

Part II: Cells vary in size, shape, and function (90 minutes):

7. Introduce cell differentiation and why its significant.
8. Group work- Name five types of specific cells you find in your body and list their functions and size (length). Use resources to look them up if you need to. Alternative: You can assign students several cells and make sure there are no duplicates. Then the students can report out on their findings.
9. Have the students observe the specific cells under the microscope. Briefly sketch them.
10. Have the students describe how the cells' characteristics relate to their function in the tissue and human body.
11. Have the students compare the cell sizes by creating a larger scale model (1nm=1inch); use masking tape to represent each cell length
12. Facilitate a discussion on cell types and how they vary in size, shape, and function. Ask the students how their first cell drawing from the introduction compares to the specific cell types they saw using the microscope. Emphasize models limitations on scale and variability.

Figure D.1. continued.

Part III: Conclusion: Cells are complex (20 minutes):

3. Show a cell animation video: *Making the Complex Simple* © XVIVO (https://vimeo.com/32267403)
4. Lead a discussion in how cells contribute to the entire human body and the importance of their similarities and differences that allow us to function.

Alternative ending/Extension:

4. Give an example of a cell malfunctioning, have the students predict its effect on the tissue, and how it manifests into a whole body disease (e.g. demyelination of neurons and multiple sclerosis).
5. Research stem cells- define a stem cell, what are their uses in the medical field, describe if there are ethical implications (debate ideas in class)
6. Research cancerous cells- compare a healthy cell with a cancerous cell, what makes cancerous cells devastating to our organs/health, research cancer topics (types, current research breakthroughs, treatments), interview someone you know that has been impacted by cancer, present to class

Assessments:

Pretest:

4. Rank the of size the following items: sand, bacterium, chicken egg, protein, virus, mouse nerve cell, an elephant nerve cell, red blood cell.
5. Name three things cells can have in common and three things that can vary between cell types.
6. Why do we use models in science? What are two aspects you need to know about any model before you use it?

Post-tests: See assessment document (Table E.1).

Figure D.1. continued.

Table D.1. Cell lesson assessment. Answers are in bold.

Cell Lesson Assessment	
Introduction of Topic	Question
I. What is a cell?	Cells have the following characteristics that define them as the simplest unit of life: (Circle all that apply.) A. An individual mammalian cell is able to survive in the environment **B. Cells are able to reproduce** **C. Cells convert energy** **D. Cells are the structural components that make up all living things** **E. Cell types vary in function and structure that allow tissues and organs to specialize in bodily functions**
II. All cells perform similar functions to survive	Circle all the functions that most cells must carry out to survive: **A. Cellular respiration** **B. Protein synthesis** **C. Endocytosis** D. Mitosis E. Meiosis **F. Exocytosis** **G. Vesicle transportation**
III. Cells vary in function	Identify the proper match of cell type and function: A. Muscle cells transmit electrical signals allowing for muscle bodies to contract **B. Skin cells produce keratin to provide a barrier from the outer environment** C. Neurons connect muscles to the spinal cord to allow for communication D. Bone cells form the skeleton and they do not change or grow in adults
IV. Cells vary in size	Rank the following objects by small to large: 1 sand, 2 bacterium, 3 chicken egg, 4 protein, 5 virus, 6 mouse nerve cell, 7 an elephant nerve cell, 8 red blood cell. A. 4, 5, 2, 6, 1, 8, 7, 3 B. 5, 4, 2, 6, 8, 1, 7, 3 **C. 4, 5, 2, 8, 6, 1, 3, 7** D. 8, 4, 5, 2, 6, 7, 1, 3
V. Cells are dynamic in nature	Circle the correct statement about cells (there may be more than one answer): A. Cells never move through tissue B. Only cells with flagella or cilia are able to move **C. Cells use chemical signals and receptors to navigate** D. Cell organelles do not move inside the cell E. Cells only move in blood vessels

Table D.1. continued.

VI. Compare and contrast cell models/diagrams	Identify the cons to using a textbook cell diagram. You can choose more than one answer: A. Too much detail and hard to visualize **B. Oversimplifies cell types** **C. Two-dimensional** **D. Portrays cells as static units** E. Demonstrates cellular organelles within the cell
VII. Ethical topics related to cells	Cell differentiation dictates whether a cell will be the following: A. Stem cell B. Cancerous cell **C. Muscle cell** D. Enzyme Malignant cancer cells have the following characteristics: (Circle all that apply.) **A. Decline in apoptosis** B. Increase in apoptosis **C. Rapidly divide** D. Decline in division E. Increased cellular differentiation **F. Decreased cellular differentiation**

BIBLIOGRAPHY OF AUTHOR

Milissa (Lewis) Knox was born in Portland, Maine on May 11, 1986. She was raised on a small farm in Buxton, Maine and graduated valedictorian from Sacopee Valley High School in 2004. She attended the University of Maine and graduated in 2008 with a Bachelor's degree in Kinesiology and Physical Education. She began the Masters of Science in Teaching program in 2008 at the University of Maine. In 2012, Milissa began a Doctorate of Veterinary Medicine degree at Washington State University and is a candidate for the Doctorate of Veterinary Medicine degree in May 2016. Milissa is a candidate for the Master of Science in Teaching degree from The University of Maine in December 2015.