ABSTRACT

MINOGUE, JAMES. The Impact of Haptic Feedback on Students' Conceptions of the Cell. (Under the direction of Dr. M.G. Jones)

The purpose of this study was to investigate the efficacy of adding haptic (sense of touch) feedback to computer generated visualizations for use in middle school science instruction. Current technology allows for the simulation of tactile and kinesthetic sensations via haptic devices and a computer interface. This study, conducted with middle school students ($n = 80$), explored the cognitive and affective impacts of this innovative technology on students' conceptions of the cell and the process of passive transport.

A pretest-posttest control group design was used and participants were randomly assigned to one of two treatment groups ($n = 40$ for each). Both groups experienced the same core computer-mediated instructional program. This *Cell Exploration* program engaged students in a 3-D immersive environment that allowed them to actively investigate the form and function of a typical animal cell including its major organelles. The program also engaged students in a study of the structure and function of the cell membrane as it pertains to the process of passive transport and the mechanisms behind the membrane's selective permeability.

As they conducted their investigations, students in the experimental group received bi-modal visual and haptic (simulated tactile and kinesthetic) feedback whereas the control group students experienced the program with only visual stimuli. A battery of assessments, including objective and open-ended written response items as well as a haptic performance assessment, were used to gather quantitative and qualitative data regarding changes in students' understandings of the *cell concepts* prior to and following their completion of the instructional program. Additionally, the impact of haptics on the affective domain of

students' learning was assessed using a post-experience semi-structured interview and an attitudinal survey.

Results showed that students from both conditions (Visual-Only and Visual + Haptic) found the instructional program interesting and engaging. Additionally, the vast majority of the students reported that they learned a lot about and were more interested in the topic due to their participation. Moreover, students who received the bi-modal (Visual + Haptic) feedback indicated that they experienced lower levels of frustration and spatial disorientation as they conducted their investigations when compared to individuals that relied solely on vision. There were no significant differences measured across the treatment groups on the cognitive assessment items. Despite this finding, the study provided valuable insight into the theoretical and practical considerations involved in the development of multimodal instructional programs.

THE IMPACT OF HAPTIC FEEDBACK ON STUDENTS' CONCEPTIONS OF THE CELL

by

JAMES MINOGUE

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DEDICATION

To my wife, Stacie, who has provided the much needed solace, guidance, and support that has made this journey possible and enjoyable; to my parents who have always encouraged me to continue my education and who have taught me, by example, the value of completing a project.

BIOGRAPHY

James Minogue was born to James E. Minogue and Theresa A. Minogue in 1972. He was raised, along with his two older sisters Patti and Theresea, in Staten Island, New York. He attended a Catholic grade school, where he received the comprehensive and structured instruction he needed before entering high school. James went to Tottenville High School, a large public school that allowed him to explore several areas of interest such as literature and mechanical drafting. While here James was active in numerous school sponsored clubs including their ski club and was a member of the National Honor Society.

Upon graduation in 1990 James attended East Stroudsburg University (ESU) of Pennsylvania where he met his future wife. While at ESU he remained active in intramural sports and joined a fraternity while pursuing a dual degree in biology and marine science. His studies engaged him in numerous summer sessions at Wallops Island, Virginia where he gained hands-on experiences in oceanography, marine biology, and coastal ecology. After earning his B.S. in 1994 James decided to explore a career in education and remained at ESU to start this work. He began taking education courses that summer and student taught the following spring; receiving his PA secondary education science certification in May of 1995.

James' first teaching position was at Leonardtown High School in St. Mary's Country, Maryland. Here he taught 9th and 10th grade biology and chemistry and benefited greatly from a group of passionate and effective teachers in the department who served as unofficial mentors. Attracted in part to the three major universities, James accepted a position teaching middle school science at Carrington M.S. in Durham, North Carolina for the next school year. Here he joined a dynamic, passionate, and innovative team of teachers that helped him grow enormously both personally and professionally. He taught 7th and 8th grade science here from 1996 until 2000. During which time he completed his M.Ed. in secondary education from East Stroudsburg University (1997) and soon after (1999) enrolled at North Carolina State University (NCSU) to begin work on his Ph.D. in science education. In 2000, James and his team of teachers moved to Lowe's Grove M.S. in Durham where he taught 7th grade science for three more years before returning to NCSU to complete his degree full-time. In June of 2001 James married his love from freshman year at ESU and they purchased a home together in Raleigh, North Carolina.

Since joining Dr. Gail Jones in the fall of 2003 James has been immersed in the thriving research and innovating teaching culture at NCSU. His work has involved him in the writing of large grant proposals, new teacher preparation and supervision, as well as cutting edge research and dissemination of results. James is excited about his future as a science educator and even more excited about the baby that he and his wife, Stacie, are expecting this summer.

ACKNOWLEDGEMENTS

The author would like to express his gratitude to a number of individuals that have provided the necessary support and guidance during his studies and culminating research project. First and foremost his advisor and committee chair, Dr. Gail Jones. I feel that one of the keys to a person's success in any endeavor is the ability to identify, value, and lean from a mentor; I am very fortunate to have had the opportunity to benefit from the insight, wisdom, drive, and passion that Dr. Jones possesses. She has provided me with a multitude of opportunities to grow professionally and instilled in me a confidence and desire that I am truly grateful for.

I would also like to acknowledge the other members of my advisory committee including Dr. Carter, Dr. Park, and Dr. Meyer who, by example, helped me to better understand what it means to model effective instruction at the university level. To Dr. Wiebe, who pushed me to explore areas of the research that I was reluctant to on my own and helped me to untangle, understand and organize this material effectively. To Dr. Annetta, who as a new faculty member, through his work ethic and kind manner, has become a model for me as I embark on my new career.

I would also like to thank Dr. Oppewal and Mrs. Broadwell who were instrumental in the planning of this research and more importantly perhaps, willing to help me in the data collection and initial analysis. To the faculty and staff at Lowe's Grove middle school for allowing me to return and conduct my study with their students; in particular Ms. Everett and Mrs. Sosna who were willing to deal with disruptions to their normal classroom routines so that their students could participate in the study.

Additionally, I would like to acknowledge the technical expertise that was provided by Dr. Bokinsky, who did the programming for our computer-mediated instructional program and Dr. Taylor whose knowledge of haptics was indispensable.

A special thank you to my former team members with whom I taught for seven years. The guidance, care, support, and insight that Mrs. May, Mrs. Wilson, and Mrs. Kempf gave me during our time together helped me grow enormously as a teacher and as a person.

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Introduction

Purpose and Significance of the Study

Computer-mediated instructional technologies hold great promise for use in educational settings in that they can increase students' access to knowledge and act as vehicles that may promote learning. Many science education researchers assert that simulations and computer-based models are an extremely powerful resource for the advancement and application of science (e.g., Linn, 1997; 2003). The progression from static 2-D images in an inert medium to dynamic 3-D models in an interactive environment has the potential to profoundly change the nature of inquiry in science and science teaching. Students immersed in interactive computer 'microworlds' may acquire hands-on and minds-on experiences that allow them to develop a deeper understanding of science concepts (White, 1992; Bransford, Brown & Cocking, 1999).

Of the five sensory channels-sight, sound, taste, smell, and touch, it is only our sense of touch that enables us to modify and manipulate the world around us. Our sense of touch is an active, informative, and useful perceptual system (Klatzky & Lederman, 2002). From our earliest days we use information gained through touch to learn about our environment and build the foundations for a wide range of concepts and understandings. Taylor, Lederman and Gibson (1973) suggested that something touched is more real than something seen. But despite its perceptual power and the wealth of information it affords us, the sense of touch has emerged as an understudied and perhaps underutilized sensory modality in the development of computer-mediated teaching tools.

There exists a growing body of research investigating the use of multimedia/computer-mediated instruction in the promotion of students' understandings of science concepts (e.g., Kozma & Russell, 1997; Barnea & Dori, 1999; Mayer, 1999; Wu, Krajcik & Soloway, 2001; Dilek & Akaygun, 2004). The results of such work assert that well-designed computer-generated visualizations and instructional units can be an effective means to enhance students' ability to conceptualize and make meaning of complex topics in school science. To date, however, the bulk of this research focuses on instructional interventions that make use of only verbal and visual stimuli. Consequently, much of what is currently known about the cognition of multimedia-based and computer-mediated learning focuses on how visual and verbal information is selected, organized, and integrated by students (Mayer, 1996). Additionally, the vast majority of these studies have been conducted within the context of physics and chemistry instruction. Although students' understandings of biological processes have been investigated quite extensively (Brumby, 1982; Dreyfus & Jungwrith, 1989; Marek, 1986; Westbook & Marek, 1991; Odom & Barrow, 1995; Sanger, Brecheisen & Hynek, 2001), few studies have involved the use of computer-mediated instructional tools.

Current technology now makes it possible to extend students' interactions with their learning environments by incorporating the sense of touch. Haptic devices, providing simulated tactile and kinesthetic force feedback, allow the user to not only see but also "feel" and manipulate three-dimensional virtual objects. Revesz first introduced the term *haptics* in 1931. The origins of this word can be traced back to the Greek words *haptikos* meaning *able to touch* and *haptesthai* which translates to *able to lay hold of* (Revesz, 1950; Krueger, 1989).

Today the term, in its broadest sense, encompasses the study of touch and the human interaction with the external environment via touch. The field of haptics has grown dramatically as haptic researchers are involved in the development, testing, and refinement of tactile and force feedback devices as well as supporting software that allow users to sense ("feel") and manipulate three-dimensional virtual objects (McLaughlin, Hespanha & Sukhatme, 2002). In addition to basic psychophysical research on human haptics, work is being done in application areas such as surgical simulation, medical training, scientific visualization, and assistive technology for the blind and visually impaired. However, due to its relatively recent advent, it remains unclear how the addition of haptics influences students' construction of knowledge and meaning making.

What haptic information do students find salient and subsequently attend to? How is this multimodal information organized and integrated? Does the unique bi-directional exchange of information between a user and a haptic device somehow enhance the learning experience? Is it possible to know something more completely by touching it?

This study attempts to answer such overarching questions by examining the impact of the haptic augmentation of a computer-mediated instructional program on middle school students' conceptions of the cell. Here the *cell concepts* are informed by national (AAAS, 1993; NSES, 1996) and state science standards' (NCDPI, 2004) recommendations as to what secondary students should know about cellular structure and functioning at the various levels of their education. Particular attention is given to the structure of the cell and its membrane, as well as the mechanisms behind the membrane's selective permeability. Consideration is also given to prior research describing middle and high school students' understandings of the cell and the process of diffusion (Dreyfus & Jungwirth, 1988; 1989; Westbrook & Marek, 1991; Flores & Tovar, 2003).

Thus, the significance of this study lies in its potential to add insight into two areas of science education that warrant further investigation: students' learning about biological concepts in a computer-mediated or computer-based environment and how the addition of the sense of touch via a haptic (simulated kinesthetic and tactile feedback) interface to such a learning environment affects students' learning.

Research Questions

The aim of this research study was to investigate the efficacy of the haptic (the sense of touch) augmentation of a computer-mediated instructional program on middle school students' understandings of *cell concepts*. To this end the specific research questions are:

1) Does haptic feedback impact students':

- ability to recognize and name the organelles found in a typical animal cell?
- identification of the corresponding functions of an animal cell's organelles?
- knowledge of the process of diffusion?
- descriptions of the molecular structure of the cell membrane?
- understandings of the mechanisms involved in passive transport and the cell membrane's selective permeability?

2) Does haptic feedback influence the way in which students select, organize, and integrate information about cell structure and functioning presented in the instructional program to construct understandings?

3) Are there differences in students' attitudes toward the instructional program for those who receive visual and haptic feedback compared to those who receive only visual feedback?

4) Is there a differential impact of the instructional program, with and without haptic feedback, according to students' gender, spatial ability, or amount of computer use outside of school?

Computer-mediated instructional technologies can enhance student performance when they are integrated into the curriculum, but the mere existence of these tools in the classroom does not guarantee that student learning will improve (Bransford, Brown & Cocking, 1999). This is particularly true in the case of haptics. The viability of this innovative technology may ultimately be determined using knowledge about human cognition in this type of a multimodal computer-mediated learning environment in accordance with practical knowledge about student learning in the complex milieu of today's classrooms.

Definition of Terms

Multimedia-based instruction: the use of some form of technology to present and combine text, graphics, audio and video. It often incorporates links and tools that let the user navigate, interact, create and/or communicate.

Computer-mediated instruction**:** the use of a computer to deliver training and other educational materials including tutorials, simulations, and exercises. It is often used interchangeably with *computer-based* instruction.

Multimodal**:** refers the involvement of more than one type of sensory channel in the conveying or acquiring of information.

Haptics**:** the science of applying tactile and kinesthetic sensation to human interaction with computers.

Haptic devices**:** force feedback devices enabling human-computer interaction via the kinesthetic and/or tactile sense.

Cell concepts: the instructional objectives of the computer-mediated program used in this study including those outlined below.

Students' ability to:

- Represent the form of an animal cell and its parts as it relates to its function.
- Recognize and name the major organelles in a typical animal cell and identify its corresponding function.
- Describe the bilipid structure of the animal cell membrane.
- Explain the mechanisms behind the selective permeability of the cell membrane as it pertains to the process of passive transport.
- Provide a scientifically sound description of the process of diffusion.

National science standards recommendations**:** According to *The National Science Education Standards* (NSES, 1996, p. 156), grade 5-8 students should understand that:

- All organisms are composed of cells--the fundamental unit of life. Most organisms are single cells; other organisms, including humans, are multicellular.
- Cells carry on the many functions needed to sustain life. They grow and divide, thereby producing more cells. This requires that they take in nutrients, which they use to provide energy for the work that cells do and to make the materials that a cell or an organism needs.

Grade 9-12 students should understand that (NSES, 1996, p. 184):

- Cells have particular structures that underlie their functions.
- Every cell is surrounded by a membrane that separates it from the outside world.
- Inside the cell is a concentrated mixture of thousands of different molecules which form a variety of specialized structures that carry out such cell functions as energy production, transport of molecules, waste disposal, synthesis of new molecules, and the storage of genetic material.

The *Benchmarks for Science Literacy* (AAAS,1993, p. 112) suggest that by the end of the 8th grade, students should know that:

- Within cells, many of the basic functions of organisms, such as extracting energy from food and getting rid of waste, are carried out.
- The way in which cells function is similar in all living organisms.

- About two thirds of the weight of cells is accounted for by water, which gives cells many of their properties.

By the end of the 12th grade, students should know that (AAAS, 1993. p. 113):

- Every cell is covered by a membrane that controls what can enter and leave the cell.
- Within every cell are specialized parts for the transport of materials, energy transfer, protein building, waste disposal, information feedback, and even movement.

State science standards recommendations:

The state's *Science Standard Course of Study and Grade Level Competencies* (NCDPI, 2004, p. 89) state:

Grade 8- COMPETENCY GOAL 6: The learner will conduct investigations, use models, simulations, and appropriate technologies and information systems to build an understanding of cell theory.

Objectives:

6.01 Describe cell theory:

- All living things are composed of cells.
- Cells provide structure and carry on major functions to sustain life.
- Some organisms are single cell; other organisms, including humans, are multi-cellular.
- Cell function is similar in all living things.

6.02 Analyze structures, functions, and processes within animal cells for:

- Capture and release of energy.
- Feedback information.
- Dispose of wastes.

High School Biology- COMPETENCY GOAL 2: The learner will develop an understanding of the physical, chemical and cellular basis of life (NCDPI, 2004, p. 100).

Objectives:

2.02 Investigate and describe the structure and functions of cells

2.03 Investigate and analyze the cell as a living system including:

- Movement of materials into and out of cells.

Chapter Two

Review of the Related Literature

Overview

The literature that is pertinent to this study is drawn from prior research in three key areas. First, previous studies in science education that have investigated students' understandings of the biological concepts of the 'cell' and the process of 'diffusion' will be discussed. This work has been conducted with individuals that span the educational sequence, from elementary school to college, and collectively suggest that the majority of learners studied find these topics difficult to construct meaningful understandings of and conceptualize.

Due to the nature of the instructional program utilized in this study, the second discipline within the literature from which information is garnered is that of educational psychology. More specifically, the research focusing on the cognition of students in multimedia/computer-based learning environments will be examined. Lastly, the research on haptic perception will be synthesized. Again, due to the nature of the instructional program and the user interface of this study, particular attention will be given to what is currently known about the selection, organization, and integration of haptic information gained through the active exploration of objects in the presence of vision. Several previous studies that have investigated the impact of haptic augmentation, within the context of learning, will be highlighted.

Students' Understandings of the Cell

"The cell is the ultimate irreducible form of every living element, and...from it emanates all the activities of life both in health and in sickness." (Virchow,1858, p. 8)

The *National Science Education Standards* (NSES, 1996) put forward that teachers should assist students in the development of more complete understandings about science and technology, as well as personal and community health. Certainly the study of cells is central and necessary to the learning about some of the most important topics in these areas. Cell biology offers the opportunity to examine long-understood phenomena related to the structure and function of living things and to explore quickly emerging ideas and technologies related to the use of cells to enhance our health. However, research has shown that many school age students possess notions about basic biological principles that are incongruent with the scientific view of the concepts (e.g., Bell, 1981; Brumby, 1982; Songer & Mintzes, 1994). Moreover, the prevalence and persistence of these 'misconceptions' or 'alternative conceptions' makes learning about complex concepts like an animal 'cell' and 'diffusion' difficult for most.

A shift in the literature, from the study of students' understandings of physical science concepts to those related to biological concepts, appears around 1981 (Westbrook, 1987). In a diagnostic evaluation study conducted with 219 tenth grade students (16 years old) in Israel, it was found that students did not have a 'general functional idea of the living cell as the basic unit of life,' as called for by curricular expectations (Dreyfus & Jungwirth, 1988). They report an "alarming level of non-internalization of the salient aspects of the topic, 'the living cell'." (Dreyfus & Jungwirth, 1988, p.229). More alarming perhaps is that these students had been taught this topic during the prior school year. The research reveals that one source of confusion may be due to students' tendency to take an anthropomorphic view of cell processes (Tamir & Zohar, 1991). For example, ideas like 'the cell *knows* what to take in and what to discard' were found to be widespread (Dreyfus & Jungwirth 1988, 1989).

Other problems seem to lie in students' difficulty in conceptualizing the spatial and metrical representations of cells; resulting in confusion between cells, atoms and molecules. Additionally, students have difficulty understanding that the cell is an autonomous organism, able to carry out the basic processes necessary for life. In particular, the establishment of relationships between cell structures and their functions are especially complex for students who are not able to *integrate* them into an overall picture of the cell (Flores & Tovar, 2003).

Even if students are able to recognize that the cell is the structural unit in which organisms are formed they still have difficulties with the cell's internal structure. The names of the organelles are known but not their corresponding function; it seems that in the students' minds cell organelles have unknown roles causing them to often rely on assigning to the nucleus all of the functions (Flores & Tovar, 2003). Marek (1986) found that only 15.8% of 60 tenth grade biology students demonstrated a sound scientifically acceptable understanding of the cell. Here, a significant number (56.1%) of students either gave no response or revealed specific misconceptions of the concept of the cell. More strikingly perhaps is that this same study revealed that 62.5% of the students either gave no response or revealed specific misconceptions about the process of diffusion and only 1.8% of the same sample showed a sound understanding of the process (Marek, 1986).

Students' Understandings of Diffusion

Diffusion is a process that crosses the disciplinary boundaries of chemistry and biology, which in itself seems to exacerbate students' conceptual difficulties. Despite the fact that diffusion is readily experienced in everyday life and is easily demonstrable in a classroom, a clear understanding of the process seems to elude many school age students. This difficulty may arise from the need to visualize the molecular events that govern the process (Westbrook & Marek, 1991). Westbrook and Marek's (1991) cross-age study of students' understanding of the process found that, regardless of the level of schooling, 'alternative' or 'misconceptions' were prevalent. Students were asked to explain 'what would happen when several drops of blue dye were added to a container of clear water…name and describe the process in as much detail as possible' and the analysis of their responses revealed that 55% of the 7th graders, 65% of the 10th graders, and 61% of the college students held 'misconceptions' about the process of diffusion. None of the 300 students' responses indicated a 'complete' or 'sound' understanding. The responses to Conceptual Evaluation Statements (CES), like the one above, of the college students were more sophisticated. These students employed more scientific terminology but the use of these terms seemed to undermine students' understandings. That is, the upper level students had been exposed to more content and vocabulary but this did not necessarily translate into a better understanding of the concept. In fact, terms like *dissolve*, *disperse*, *surface tension*, and *density* were often misused in their explanations of 'diffusion.'

Another study (Odom, 1995) had 116 secondary biology students, 123 college non-biology majors, and 117 biology majors take the *Diffusion and Osmosis Diagnostic Test* (DODT) developed by Odom and Barrow (1995). This two-tiered multiple choice instrument presented questions in pairs, with the first asking a content question about diffusion or osmosis (e.g. 'During the process of diffusion, particles will generally move from. . . ') and the second asking for a reason for the answer chosen for the first (e.g. 'The reason for my answer is because . . . '). The intent of this questioning format was to reveal the students' content knowledge, as well as their understanding of that knowledge. The results of this investigation showed 'misconceptions' in five of the seven conceptual areas measured by the test: the particulate and random nature of matter, concentration and tonicity, the influences of life forces on diffusion and osmosis, the process of diffusion, and the process of osmosis.

The studies discussed commonly suggest that more effective methods are required to teach these difficult concepts. This assertion was tested by Christianson and Fisher (1999) when they compared students' understanding of diffusion and osmosis, in three non-major biology courses at three different universities. The first two courses followed a traditional pattern of instruction, with lectures given in large halls to all of the students enrolled in the course and laboratory experiences in smaller sections. The third course was an integrated laboratory/discussion class that employed inquiry and discovery-based teaching, instructional strategies common to constructivist learning (Tobin, 1990; Brooks & Brooks, 1993). The DODT instrument (previously described) was administered pre- and post-instruction. The scores indicated significant learning differences, with students in the small constructivist influenced discussion/laboratory course learning about and understanding diffusion and osmosis 'most deeply' (Christianson & Fisher,1999).

This notion that different (and perhaps more effective) teaching methods can impact students' understandings of the process of diffusion was further supported by a more recent study (Sanger, Brecheisen & Hynek, 2001). The purpose of this work was to determine whether viewing computer animations depicting the molecular processes of diffusion and osmosis would affect students' conceptions of these topics. Again, the students' understandings were measured using the DODT instrument. This study involved 149 students from a second-semester introductory college biology course. All of these students attended the same lecture section which met for three hours per week; each student was also enrolled a laboratory section containing 21 to 28 students. This research took place in the laboratory sections after the students had received instruction on diffusion and osmosis during lectures. Students were randomly assigned to one of two treatment groups. Both groups performed several experiments including the diffusion of potassium permanganate in water, the osmosis of water and glucose (but not starch) through cellulose dialysis tubing, and the effect on the cells of an *Elodea* leaf after being placed in hypotonic, isotonic and hypertonic solutions (Sanger, Brecheisen & Hynek, 2001). However, students in the experimental group viewed two animations explaining the molecular behaviors associated with the processes of diffusion before performing these experiments while the control group did not.

The results showed that students who viewed the animations were less likely to choose responses on the DODT suggesting that particle motion stops after equilibrium is reached. It was assumed that these animations were successful in helping students understand the dynamic nature of equilibrium processes. Additionally, students in the experimental group were less likely to attribute molecular motions to anthropomorphic 'desires' of the molecules. More students (47% versus 32%) in the control group, having not viewed the animations, believed that as the difference in concentration increases between two areas, the rate of diffusion increases because the molecules 'want to spread out' than in the experimental group. (Sanger, Brecheisen & Hynek, 2001).

In summary, the literature regarding students' conceptualizations of the 'cell' and the process of 'diffusion' illustrate that, in general, students experience difficulty constructing meaningful knowledge and scientifically sound understandings. But the research also suggests that the use of instructional strategies (be they from a constructivist approach or a computer animation) that actively engage the students in the knowledge construction and meaning making process can enhance their learning. But how might such activities promote student learning of these concepts? In an effort to answer this, the review of the literature next looks at some of the research regarding student cognition of multimedia/computer-based learning.

Multimedia Computer-based Learning

As noted in the introduction, much of the work to date that has investigated how individuals *learn* in a multimedia or computer-based environment has involved instructional programs that make use of verbal and visual information only. Although the present study is distinctly different in that its primary aim is explore the impact of haptic (simulated kinesthetic and tactile) information on student learning; the underpinnings of a portion of this existing research does provide a framework for investigating this type of multimodality.

One cognitive theory of multimedia/computer-mediated learning is centered on three basic premises from research in cognitive science: *dual channels*, *limited capacity*, and *knowledge construction* (Mayer, 1997; 2003). The first notion is that humans are dual channel or code processors. More specifically, people have separate channels for processing verbal and nonverbal information (Paivio, 1986). Piavo's (1996) dual coding theory (DCT) is thought to be one psychological mechanism that permits unified explanations of diverse (cognitive and affective) educational phenomena (Clark & Piavio, 1991). According to the DCT our *verbal system* receives and maintains visual, auditory, and articulatory verbal codes. These verbal word-like codes are arbitrary symbols that denote concrete objects and events as well as abstract ideas. The codes retain separate and discrete identities even when connected to one another and are processed in a serial or sequential manner. Conversely, our *nonverbal system* contains modality-specific images for shapes, sounds, actions, sensations, and other non-linguistic events. Unlike nonverbal information, these are not arbitrary symbols but representations that are analogous and perceptually similar to the events they denote. In addition, these non-verbal representations are processed in a parallel or simultaneous manner (Piavio, 1986).

The second component of the theory is that humans have a limited capacity for processing information from their environment, be it verbal or nonverbal in nature. Information is initially received by the extremely short-term sensory memory. These sensory memories act as buffers for stimuli received through the senses. A sensory memory exists for each sensory channel: *iconic memory* for visual stimuli, *echoic memory* for aural stimuli and *haptic memory* for touch (Baddeley, 1999). Information is then passed from sensory memory into working or short-term memory by attention, thereby filtering the stimuli to only those which are of interest at a given time. People are able to actively process only a small amount of information from each of the channels at any one time (Sweller, 1994; 1999). This is commonly referred to as the cognitive load theory (CLT) and it assumes that for effective information processing, users need to reduce all unnecessary cognitive loads on their working or short-term memory (Sweller, 1994). It is thought that one way to achieve such load reduction is to present information using multiple channels or modalities (Mousavi, Low & Sweller, 1995). The present study introduces a third sensory channel for touch, the affects of which are still unclear.

The last element of this cognitive theory is that humans *construct knowledge* and due to this, ‘meaningful learning’ takes place when people attend to relevant incoming information, mentally organize the information into coherent structures, and mentally integrate it with their prior knowledge. This process is illustrated in Figure 2.1 for a multimedia learning environment that provides verbal and visual stimuli.

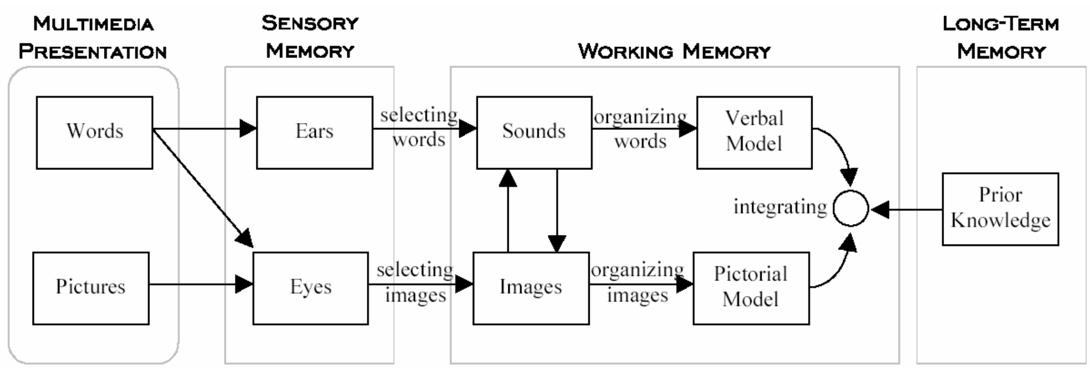

Figure 2.1. A cognitive model of multimedia learning proposed by Mayer (1996;1997).

This above SOI model, put forward by Mayer (1996;1997), suggests that the learner engages in three important cognitive processes; the first of which is s*electing*. Here, the learner pays attention to and selects relevant information for further processing. The second cognitive process, *organizing*, is essentially the building of ‘links’ among and between the selected and retained information. Piavio (1986) called these ‘links’ *connections* and maintains that there are two distinct types. *Referential connections* link verbal and nonverbal representations from a complex network of *associative connections*, the ‘links’ within the two individual systems. Finally, the third process, *integrating*, occurs when the learner builds one-to-one connections between corresponding elements, events, states or parts of these representations using prior knowledge in an attempt to make meaning of what has been perceived (Mayer, 1996; 1997). One of the challenges of the present study is better understanding how haptic information plays into the above described cognitive theory.

One can reasonably conclude that haptic information, gained through the sensory modality of touch, is nonverbal in nature. Consequently, one can assume that this haptic information is processed and stored in the nonverbal or image based region of our working or short-term memory. Moreover, there is a considerable amount of evidence indicating the type of haptic information individuals find particularly salient and select to process (e.g., Klatzky, Lederman & Matula, 1991;1993; Klatzky & Lederman, 2000). What is less clear, however, is the representational form that selected haptic information takes as an individual attempts to organize this information in memory. Additionally, the way in which this kind of sensory information is integrated as an individual 'makes meaning' of perceived objects and events is still largely unknown.

Haptic Perception and Selecting Information

"Touch provides information on the innards of objects, whereas the eye, remaining fixed on the outer surface of objects, plays a lesser role in developing the belief in the reality of the external world." (Krueger, 1989, p.3)

The sensory channel of touch receives information, not just sensations (Kennedy, Gabias & Heller, 1992). Heller (1982) notes Reid's early proposition (1764/1967) that the use of vision requires the learner to indirectly perceive attributes such as hardness, softness, motion, and texture that are originally known directly to the tactual sense. Based on the findings of over twenty years of research into human haptic perception, Lederman and Klatzky (e.g., 1983; 1987; 1990; 1999; 2002) have been able to identify precisely the type of haptic information that individuals find relevant and *select* for further processing during object exploration.

The extensive work of these researchers has led to the development of what is known as *exploratory procedures* (EPs) (Lederman & Klatzky, 1987). EPs are a taxonomy of the stereotypical and formulaic hand movements that individuals performing haptic explorations instinctively employ in order to extract information regarding an object's properties (Figure 2.2). Each EP is associated with a particular object dimension which it is the optimal and preferred method for determining the property under unconstrained haptic exploration. An example of this is *pressure* (described as applying torque or normal forces to one part of the object while the object is stabilized) which yields information about the object's *compliance*. *Lateral motion*, associated with *texture* encoding, is characterized by production of shearing forces between skin and object. *Contour following*, where the hand maintains contact with a curve on an object, provides salient information about the *shape* and *volume* of the object. It is believed that these exploratory procedures maximize the sensory input corresponding to a certain object property, permitting increased ease of organizing and encoding (Klatzky, Lederman & Reed, 1987).

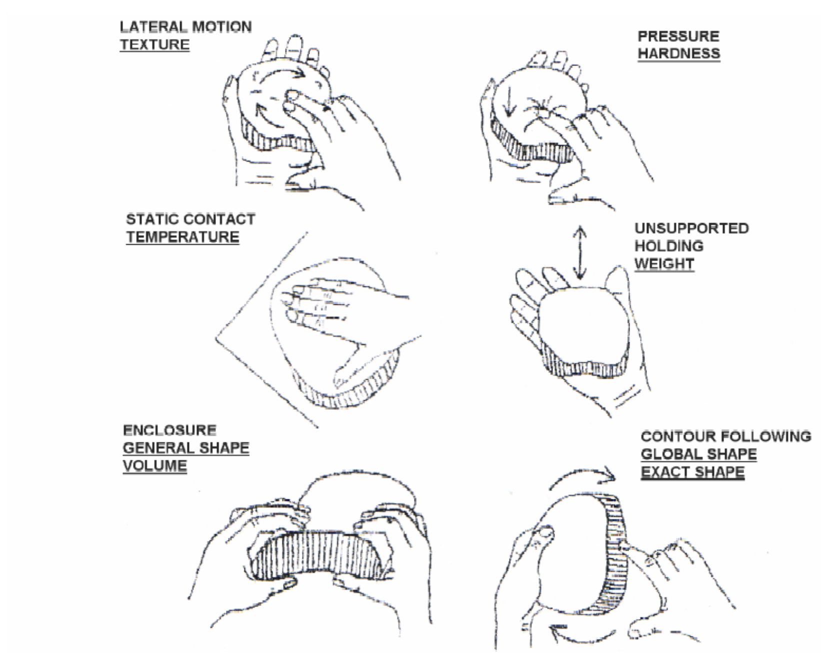

Figure 2.2. A depiction of the exploratory procedures (EP) as described by Lederman & Klatzky (1987). Permission to reprint received from author.

It is important to note that the experimental results, on which these *exploratory procedures* are based, are derived from studies that allowed subjects to actively explore and manipulate *real objects*, both with and without the use of vision. Inherently, the haptic device used in the present study changes the nature of this exploration and impacts the information that is available. The haptic device employed in this research permits simulation of fingertip contact with virtual objects through the point-probe of a pen-like stylus. The use of this interface allows for the creation of 3-D immersive and tangible computer visualizations of objects and events that would be otherwise difficult to touch and manipulate. However, there exists a fundamental difference between the sensory information provided by a point-probe and the information obtained through a more natural exploration of an object with one's entire hand. This disparity is a direct result of the number and size of the areas of contact between the user and the object. Table 2.1 describes the availability of EPs during 'constrained' point-probe explorations of objects.

Table 2.1

Availability of EPs During Exploration with a Point-probe

Exploratory Procedure	Description	Availability under 'point-probe' exploration with a PHANToM	Attribute of object from the instructional program sensed
Lateral Motion	Movement back and forth between skin and object surface.	Available, though cues will be temporally varying (vibration) instead of spatially varied.	Surface *texture* of cell parts. *Viscosity* of cytoplasm. *Texture* of phospholipids and protein molecules.
Pressure	Applying normal force to surface of object.	Available	*Flexibility* of cell membrane. *Compliance* of nucleus and mitochondria.
Static Contact	Resting passively without molding.	Available, though no temperature or distributed force cues are available.	Not modeled.
Unsupported Holding	Object is lifted and maintained.	Available, by attaching simulated object to distal point of probe.	Not modeled.
Enclosure	Hand maintains simultaneous contact with as much of the object as possible.	Unavailable in the absence of multiple contact points.	Not possible.
Contour Following	Smooth, non-repetitive movement with a curved surface of the object.	Available. Difficult to execute due to small contact area.	*Shape* and *size* of the cell, its organelles, and the components of the cell membrane.

The last column of this table relates these point-probe interactions to the attributes or features of the virtual objects from the instructional program used in this study. It allows the user to see and "feel" a computer-based virtual model on an animal cell, depicting the 3-D nature and spatial arrangement of an animal cell including its typical parts or organelles. The structural differences (i.e. relative size, surface area, texture, shape, elasticity & rigidity) of the parts are emphasized. At a second level, the structure and function of the cell membrane is simulated.

Klatzky, Lederman, and Reed (1987) postulated that haptics is oriented toward the perception and subsequent encoding of *material properties*. Haptics is thought to be superior to vision in perceiving properties such as texture (roughness/smoothness, hardness/softness, wetness/dryness, stickiness, and slipperiness), weight, hardness, compliance, elasticity, and viscosity (Lederman, 1983; Zangaladze et al., 1999; Klatzky & Lederman, 2000). Whereas our vision dominates in the perception of *geometric properties* like shape and size and color (Sathian et al., 1997; Verry, 1998; Klatzky & Lederman, 2000).

Given this, it is hypothesized that students in the present study will instinctually use vision to extract information regarding the shape and relative size of the cell and its organelles, even when touch is available. Conversely, it is believed that individuals will find information about the virtual objects' *material properties* salient during haptic exploration. For example the flexibility of the cell membrane, viscosity of the cytoplasm, compliance of the nucleus, and texture of the rough endoplasmic reticulum may be readily *selected* by students for further processing. Additionally, the haptic interface makes the simulation of the forces associated with the process of passive transport possible. Students can 'sense' the pull of a potassium ion through a protein channel, information that seems to be well suited for haptic perception.

Haptic Perception and Organizing Information

"In stark contrast to the voluminous literature on visual imagery, little is known about imagery associated with touch." (Klatzky & Lederman, 2000, p. 242).

According to this SOI model of cognition (Mayer, 1996), the next task the learner must engage in is *organizing* the haptic information that has been selected for encoding. Lederman and Klatzky (1987) argue that haptic *exploratory procedures* can serve as a window into our representations in memory. In both 'everyday perception' and the instructional program of this present research, touch and vision operate together but the nature and dynamics of this relationship remains uncertain.

What representational form does perceived haptic information take? Is haptic information combined with visual data to build a shared representation or are there distinct haptic images in our 'memories'? There exist three basic views that may help explain how this type of perceptual information is processed (Turkewitz, 1994). The first idea maintains that information comes from separate sensory systems via independent pathways and it is often presumed to be sensory-specific at an "early" level, a dual coding approach. At a higher (conceptual), level information from all perceptual modalities is thought to be jointly available. According to this view (e.g., Fodor, 1983) all visual processing would be independent of haptic processing and each would require its own memory storage system complete with distinct images or representations. A second notion is that perceptual information is maintained in an amodal representation (Gibson, 1966; 1979) which receives inputs from all our sensory modalities. In this view, only one *global representation* is maintained and stored. Subsequently each piece of information, no matter how detected, is included in a representation of what is perceived.

More recently, a third view that perhaps bridges the two older views is of separate but interacting perceptual modalities (Stein, Merideth & Wallace, 1994). Here information is easily exchanged and integrated such that perceptual systems may influence one another's processing. According to this view, which parallels the cognitive load theory (CLT), there is a functional organization or division of labor which allows for *cross-modal* interactions among systems which are in concert with task demands (Damasio, 1989).

There has been some effort to determine if information encountered through the sense of touch is represented in manner that is modality-specific or more general (e.g. spatial). Millar (1997) pointed to evidence for the existence of short-term memory in the tactual modality with a limiting span of two-three items (Watkins & Watkins, 1974; Millar, 1975). There is additional evidence for tactual coding during early learning of small patterns like Braille forms; coding that is in terms of tactual features such as texture or dot density, rather than being spatially mediated (Millar, 1997).

Klatzky, Lederman, and Metzger (1985) contend that the haptic modality constitutes an *expert system*. They extended this proposition by suggesting that our capacity to process information of a haptic nature is superior to vision and audition; citing that the haptic modality is not limited to a single sense organ or receptor but is instead a combination of several interrelated mechanisms; a system that is not subject to the same rapid decay of information observed for the *icon* and *echo* of very short-term sensory memory (Kiphart, Auday & Cross, 1988). Separate and distinct representations is suggested by other experiments on haptic object categorization, which indicate that people use different attributes to group objects, depending on whether the subjects are instructed to think about what the objects *feel like* vs. *look like* (Klatzky, Lederman, & Reed, 1987; Lederman, Summers & Klatzky, 1996). This sort of 'modality encoding bias' may lead to the creation of modality-specific representations (Klatzky & Lederman, 2000).

A major distinction in memory systems is that of *implicit* and *explicit* memory. Implicit memory is signified by "priming" or a change in the performance of some task, due to prior exposure to the task materials, a sort of acquired "perceptual fluency." Explicit memory is thought to be the conscious recognition or recall of objects or events using knowledge in one's memory (Tulving & Schacter, 1990). Srinivas, Greene, and Easton (1997) showed that both implicit and explicit tactual memory tests were affected by changes in the orientation and size of the forms between study and test; when the forms were left/right reversed or resized, priming produced by implicit memory vanished. In contrast, a visual version of the test was affected by orientation changes but not size changes. This suggests that the source of implicit memory in touch is not identical to that in vision, and that the functional representation in touch preserves the physical structure and scale of the touched objects.

Evidence of distinct but shared representations can be found in the research into cross-modal priming (implicit memory representation that is accessible multimodally) between the visual and haptic modalities. Easton, Srinivas and Green (1997) demonstrated substantial cross-modal priming between vision and touch with seen or felt words as stimuli, using word stem-completion as an implicit memory test. Reales and Ballesteros (1999) used common objects as stimuli and various implicit tests (speed of object naming, the level of completeness at which a fragmented picture could be identified, and speed of deciding whether a line drawing depicted a real object) to investigate implicit and explicit memory under both intra-modal (within one modality) and cross-modal conditions. Results indicated cross-modal and intra-modal priming (faster responses for previously studied objects), and in some cases the magnitude of the cross- and intra-modal priming effects were equivalent leading to the speculation that visual and haptic object representations are so similar that they might actually be shared between the two modalities.

Bushnell and Baxt (1999) demonstrated that children studied were virtually error-free at discriminating between previously presented and newly presented common objects, whether the modality changed between vision and touch or was held constant between presentation and test. This cross-modal recognition became less accurate (though still above chance levels) when the objects were unfamiliar or when the old and new objects were different examples of the same category name. The authors maintained that the categorical effect observed was likely due to mediation at a higher (conceptual) level.

Aside from the above described behavioral studies there is a growing body of neurological evidence indicating that visual and haptic object representations are so similar that they might actually be shared. Several neuroimaging studies have indicated possible interactions between the visual and haptic systems. Researchers have used functional magnetic resonance (fMRI) imaging to measure the effects of cross-modal haptic-to-visual priming on brain activation (Sathian et al., 1997; Deibert et al., 1999; Zangaladze et al., 1999; Amedi et al., 2001). Results of these studies suggest that the neural substrate underlying both visual and haptic object recognition is found within the occipital cortex associated with visual processing. This overlap in some of the neural structures mediating haptic and visual processing of object structure suggests that the haptic system may exploit the highly developed object representation systems of the ventral visual pathway.

In sum, there exists evidence that support multiple interpretations of how haptic information is *organized* in memory. It remains uncertain if there are modality-specific or combined visual/haptic representations that are involved in the final phase of knowledge construction, *integrating* the selected and 'organized' information.

Haptic Perception and Integrating Information

"It is a truism of our educational creed that sensory impressions based on object lessons and motor response form the primary basis of thought in dealing with the later materials of knowledge." (McMurray, 1921, p. 3).

There is evidence that touch is a fully cognitive system providing the basis for conscious memory and learning (e.g., Loomis & Lederman, 1986; Klatzky & Lederman, 2002); however to this point there has been very little research exploring how the addition of haptic feedback impacts the way in which individuals *integrate* this information during the 'meaning making' process. The influence that this additional sensory modality and its accompanying information have on the way in which an individual makes connections between prior knowledge and experiences to construct understandings has been understudied. The critical role of touch in 'meaning making' permeates the language that we often use to describe learning. We talk about "grasping the idea," getting a "handle on a problem," or being "touched by a reading." Many educators believe that "hands-on" experiences, ones that actively involve students in the manipulation of objects, are powerful teaching tools. Elementary school teachers have long been interested in the use of manipulatives in their lessons. Manipulatives are designed to be touched and handled by students; helping them develop their muscles, perceptual skills, psychomotor skills and providing concrete experiences with intangible concepts and ideas (Ross & Kurtz, 1993). But is it possible to know something more completely by touching it? Does involving the sense of touch enable one to construct a more connected and meaningful understanding? Can augmenting existing instruction with touch exploit experiential, tactic, and embodied knowledge, that might not otherwise be called upon?

Active touch involves intentional actions that an individual chooses to make. Sathian (1998) has suggested that involving students in consciously choosing to investigate the properties of an object is a powerful motivator and increases attention to learning. This assertion is supported by the results of an investigation into the influence of haptic feedback on middle and high school students' concepts of small objects such as viruses (Jones et al., 2003; 2004). Jones et al. (2003; 2004) reported that students who received haptic feedback as part of microscopy experiments showed significantly better attitudes, suggesting that the increased sensory feedback and stimulation made the experience more engaging and motivating to students. This increase in attention may impact what and how students select information for processing.

In addition to such affective influences, the use of multiple senses in learning is thought to be involved in the development of more generalized cognitive processes, namely moving from concrete to abstract thinking (Loucks-Horsley et al., 1990). It has been noted that "hands-on" or sensory-motor experiences are necessary elements for the subsequent development of formal operations (Wadsworth, 1989). Educators traditionally maintain that the active physical manipulation and handling of objects is often a more effective way for students to learn complex and abstract concepts when compared to more passive modes of instruction (Glasson, 1989; Vesilind & Jones, 1996; Druyan, 1997).

In further postulating about how the addition of haptics might impact 'meaning making,' further evidence emerges from the technology's increasing use in flight and medical training. Military and commercial pilots may now be trained in flight simulators, which apply forces on the controls corresponding to those occurring during actual flight. Additionally, many types of medical simulation haptic interfaces exist, particularly for laproscopic and endoscopic surgery. The virtual environments for this application can be programmed to be similar to the soft tissue inside the human body and the user can practice removing polyps and suturing tissue (Burdea et al., 1992; Jacobson, Kitchen & Golledge, 2000; Hayward et al., 2004).

It is thought that in these training scenarios the advantage of the addition of haptics is its impact on a person's kinesthetic memory (the ability to remember limb position, velocity, etc.). In a review of the research into kinesthetic memory, Clark and Horch (1986) suggest that humans have a remarkable ability to remember positions of their limbs quite accurately and for long periods. Haptic training is different from visual training in that the learning that takes place is body centered. This approach may also be useful for complex, three or more dimensional, motor skills that are difficult to explain and describe verbally or even visually. Perhaps this active type of learning, encouraged by the use of haptics, has benefits over more passive observational learning (Laguna, 2000). Seemingly, similar results can be expected in the context of the classroom.

Another feature of haptic feedback, that may have a positive impact on the *integration* of information, is its ability to tap an individual's somatic knowledge. More specifically, the idea that people gain understandings from tangible physical experience, from coming in contact with natural and built elements, and from moving through spaces (as well as from seeing objects in space) (O'Neill, 2001). The term *haptic perception* has been used in psychology to describe a holistic way of understanding three-dimensional space (Piaget & Inhelder, 1967). Haptic experiences suggest alternative ways of knowing that involve the integration of many senses, such as touch, positional awareness, balance, sound, movement, and the memory of previous experiences. These somasthetic and haptic perceptions are gained through corporeal activity and physical work. They allow us to know places in intimate, unself-conscious ways that visual sensibilities cannot describe. Such combinations of sensibilities have been referred to as *simultaneous perception*; a wide range of the experiences produced from these sources are not namable sensations, and hence have been long overlooked by researchers (Gibson, 1966). Straus (1966) defined this mind/body duality as two modes of personal experience: *gnostic* and *pathic*. The gnostic mode consists of ‘looking at’ objects as distinct from the self, and deals with cognition of the object. The pathic mode guides our perception in touching, and places emphasis on preconceptual phenomenal experiences, and the changing ways in which things appear directly to the senses as we move through space.

Kilpatrick (1976) used kinesthetic feedback as an aid to 2-D and 3-D force field understandings. He showed that kinesthetic feedback improved user perception and manipulation in a simple 3-D virtual world, even more so than did three-dimensional stereo viewing. Similarly, Brooks et al. (1990) found that understanding of the binding energy of a drug molecule was much clearer when forces were simulated using haptic feedback and added to a visual display of a simple 6-D (x, y, z, pitch, yaw, and roll) docking task. Brooks (1990) concluded that haptic augmentation of a visual display can improve the user’s perception of valid docking positions for drugs and enhance their understanding of why a particular drug docks well or poorly.

Haptic augmentation may also help students construct knowledge about “invisible” phenomenon. Clark and Jorde (2004) studied the impact of integrating a tactile sensory model into a thermal equilibrium visualization. Here the mere simulation (students in the experimental group did not actually receive any haptic feedback) of tactile feedback was associated with middle school students' improved understanding of thermal equilibrium. This tactile model did not incorporate haptics, rather it showed a hand next to the object with heat flow arrows flowing to or from the hand at varying rates depending on the temperature gradient between the hand and object in an attempt to indicate how hot or cold the object feels. In addition, the visualization used audio and text messages that described how the object feels (e.g., ''This feels burning hot!''). The results of this investigation showed that students that experienced this simulated tactile model of thermal sensation had a greater capability to describe why objects "feel" the way they do in regards to thermal equilibrium.

Additional evidence for the potential value of haptic stimulation in knowledge construction, meaning making, and learning is provided by a study that examined the effects of incorporating the haptic exploration of letters into a training program designed to develop understandings of the alphabetic principle among pre-reading kindergarten children (Florence et al., 2004). Here the authors note that reading acquisition is broadly thought to consist of the development of phonological and visual representations as well as the establishment of connections between these two types of representation. Yet much of the research assumes that it is an implicit process which is triggered by the learning of letter/sound correspondences.

The researchers go on to suggest that one of the difficulties in learning to read is in part due to the child's inability to establish a connection between the visual image of a word and its auditory image (Florence et al., 2004). In an attempt to overcome this difficulty, a "multisensory" learning method (largely based on Montessori's principles) involving not only on the visual and auditory modes but also the manual and active haptic modality was used. This teaching technique, known as the "multisensory trace" (Fernald, 1943), involves the children in tracing a written word with their index finger while pronouncing it and looking at it. The results of this study showed that incorporating the haptic exploration increased the positive effects of the training on the understanding and use of the alphabetic principle in young children and their decoding skills. More importantly perhaps, the haptic exploration appeared to help students establish the *referential links* between the visual representations of the letters and the phonological representation of the corresponding sounds. It was suggested that the beneficial effect of incorporating the haptic modality could be due to various functional specificities of the sensory modalities (Gentaz & Rossetti, 1999; Hatwell, Streri & Gentaz, 2003). Including the haptic exploration led children to process the letters in a more sequential and analytical way, something which they do not do implicitly when the letters are presented in a visual form only.

Perhaps the addition of haptic feedback leads to more *associative connections* among existing images and prior knowledge, helping students create more 'experiential' meanings. This notion is supported by the work of Reiner (1999) in which she examined the role of tactile perception in the conceptual construction of forces and fields by employing a modified trackball that transferred a simulated force applied by a field to the learner's hand. She presented 'embodied experiences' as a way to explain the positive educational impact of haptics. That is to say, this learning environment stirs up tacit embodied knowledge, previously unexploited non-propositional knowledge. This type of knowledge is in immediate (without the mediation of symbols and concepts) relation to objects and bodily acts. She goes on to suggest that haptic devices are interfaces that promote the use of bodily non-propositional knowledge in the building of more accurate mental models and representations.

Learning is often defined as the construction of knowledge as sensory data are given meaning in terms of prior knowledge (Lochhead, 1988; Loucks-Horsley, et al., 1990; Tobin, 1990; Brooks & Brooks, 1993). Perhaps the addition of haptics affords students the opportunity to become more fully immersed in this process of meaning making; prompting them to take advantage of tactile, kinesthetic, experiential, and embodied representations from memory in new ways.

Chapter Three

Methods

Overview

This chapter describes the research methodology used to answer the following research questions:

1) Does haptic feedback impact students':

- ability to recognize and name the organelles found in a typical animal cell?
- identification of the corresponding functions of an animal cell's organelles?
- knowledge of the process of diffusion?
- descriptions of the molecular structure of the cell membrane?
- understandings of the mechanisms involved in passive transport and the cell membrane's selective permeability?

2) Does haptic feedback influence the way in which students select, organize, and integrate information about cell structure and functioning presented in the instructional program to construct their understandings?

3) Are there differences in students' attitudes toward the instructional program for those who receive visual and haptic feedback compared to those who receive only visual feedback?

4) Is there a differential impact of the instructional program, with and without feedback, according to students' gender, spatial ability, or amount of computer use outside of school?

This methodology includes a discussion of the research design, followed by a description of the study site and its participants. Next, the computer-mediated instructional program and the user interface employed in the study are described. In addition, details about the instrumentation including their source, as well as validity and reliability information are given. The procedural details, from the perspective of an individual participant, are also outlined. A description of the research hypotheses, the scoring of the data generated for each hypothesis, and the analysis plan for the data are included. Finally, additional sources of data and their analyses are briefly discussed.

Research Design

This exploratory study employed a randomized pretest-posttest control group design to investigate the impact of haptic feedback on students' understandings of the *cell concepts* as described in the first chapter. Participating students were randomly assigned to one of two treatment groups. Both groups experienced the same core computer-mediated instructional program, the *Cell Exploration* (described further below). Students in the experimental group received bi-modal (visual and haptic) feedback as they completed the program. Conversely, members of the control group only received uni-modal (visual) information as they worked through the activity.

Study Site and Participants

This study was conducted at an urban middle school in central North Carolina that served predominately low income (68% qualify for free or reduced lunch) students. The participants (n = 80) were drawn from 4 of the 12 intact seventh grade integrated science classes. This sample was comprised of 37 females and 43 males with an ethnic composition of: 5% Asian, 18 % Caucasian, 19% Hispanic, and 58 % African American. The students were randomly assigned to either the experimental or control group (n = 40 each). These treatment groups are described in more detail in the section that follows.

Instructional Program

The computer-based *Cell Exploration* instructional program was designed to allow students to follow on-screen instructions which prompted them to explore the structure and function of a typical animal cell. The exploration began with a computer generated virtual model that depicted the 3-D nature and spatial arrangement of an animal cell with its characteristic organelles. The program allowed students to rotate and zoom in or out on the image of the cell being modeled. The structural differences of the parts were emphasized. As students conducted their survey of the cell and encountered the various structural components with a point probe, descriptions of the parts appeared in a text box on the screen, as depicted in Figure 3.1 below.

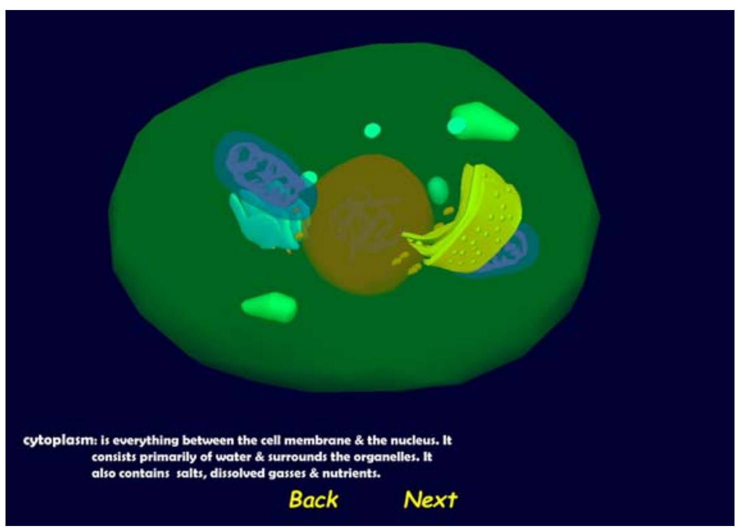

Figure 3.1. A screenshot of the *Cell Exploration* instructional program.

Next, students viewed an animation that described the cell's environment, the structure of the cell membrane, as well as the processes of simple and facilitated diffusion. Following the animation, students were given the opportunity to further investigate the structure of the cell membrane in a manner similar to the one described for the students' investigation of the cellular organelles. This portion of the program involved another 3-D visualization that depicted the fluid mosaic model of the cell membrane and allowed the user to explore and gather information about the phospholipid bi-layer and protein construction. In the last section (shown in Figure 3.2) the program highlighted the mechanisms behind the cell membrane's selective permeability. Students investigated how certain molecules traverse the membrane via the various types of passive transport. In a game-like scenario students were prompted to try to pass these substances through the membrane and reach an equilibrium.

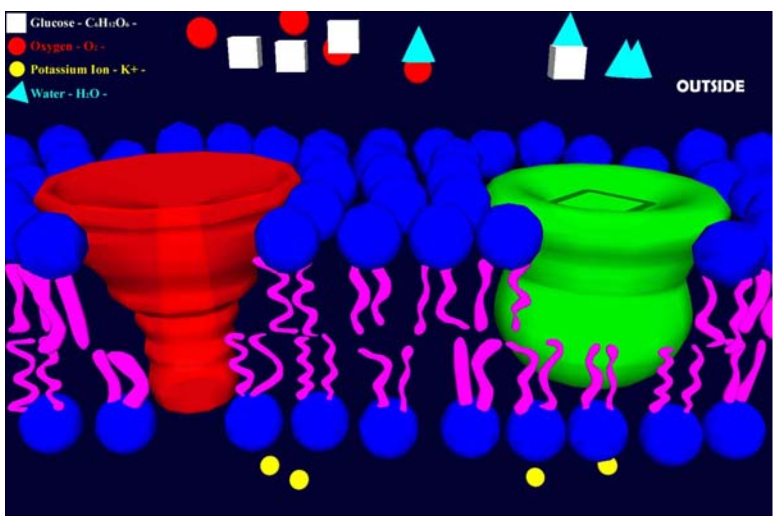

Figure 3.2. A view of the last section of the *Cell Exploration* instructional program.

It is important to note that there is no audio feedback provided during any portion of the instructional program. During the course of the study, student's progression through the program was monitored by a researcher who followed the *Cell Exploration Guide* (see Appendix A). This guide was intended to ensure that all students had a similar experience and attended to the same science content being presented.

Students in the experimental group received haptic feedback via a PHANToM desktop device (www.sensabletechnologies.com) as they conducted their investigations. The PHANToM, one of the most commonly used haptic devices, is a small, desk-grounded robot-like arm that permits simulation of fingertip contact with virtual objects through a pen-like stylus as shown in Figure 3.3. It tracks the *x, y,* and *z* Cartesian coordinates and pitch, roll, and yaw of the virtual point-probe as it moves about a three-dimensional workspace, and its actuators communicate forces back to the user's fingertips as it detects collisions with virtual objects, simulating the sense of touch (Salisbury et al., 1995).

Figure 3.3. The PHANToM desktop device from SensAble Technologies, Inc.

This unique bi-directional interface afforded the students to the opportunity to “feel” the shape, size, texture, viscosity, and elasticity of the cellular structures. In addition, during the final part of the program students were able to “feel” the forces associated with the passive transport of the substances. For example, students in this group could “feel” the potassium ion being pulled through the protein channel and “feel” how the glucose molecule fit into its protein channel, causing a conformational change in the protein.

Students in the control or comparison group used the identical computer interface (PHANToM desktop device and laptop computer); however the haptic feedback was turned off during their exploration. As a result, control group participants experienced the same core instructional program but received only visual stimuli.

Instrumentation

A battery of assessments (see Appendix B - E) was used to generate both quantitative and qualitative data from both the affective and cognitive domains of student learning. Table 3.1 summarizes the links among these data sources, the research questions, and the targeted domains of learning.

Table 3.1

Summary of the Connections Among Learning Domains, Research Questions, and Data Sources

Domain	Research Question	Data Source	Description
Cognitive ↓	*Does haptic feedback impact students' ability to recognize and name the organelles found in a typical animal cell?*	Label the cell diagram (p. 3, #4)	Pre-and Post Assessment: objective recall & recognition/selection items ↓
	Does haptic feedback impact students' identification of the corresponding functions of an animal cell's organelles?	Match the cell part with its function (p. 5, #6)	
	Does haptic feedback impact students' knowledge of the process of diffusion?	Diffusion Concept Evaluation Statement (p. 2, #3)	Pre-and Post Assessment: open-ended/supply items & drawing tasks ↓
	Does haptic feedback impact students' descriptions of the molecular structure of the cell membrane?	Draw the cell membrane (p. 6, #7)	
	Does haptic feedback impact students' understandings of the mechanisms involved in passive transport and the cell membrane's selective permeability?	Cell membrane-filter paper analogy (p. 4, #5) Selective permeability question (p. 6, # 8)	
Cognitive	*Does haptic feedback influence the way in which students select, organize, and integrate information about cell structure and functioning?*	'Tell me everything that you know about a cell' (p. 1, #1) Draw a cell (p. 1, #2)	
Affective	*Are there differences in students' attitudes toward the instructional program for students who receive visual and haptic feedback compared to those who receive only visual feedback?*	Assessment of Instructional Module (AIM)	Post-experience self-report survey

Below is a brief description of each of the assessments:

- *Student Information Sheet & Computer Use Survey*. This questionnaire (Appendix D) gathered demographic information including gender, age, and ethnic background. In addition, it provided information about students' use of computers outside of school. This instrument was designed to elicit information that could be used to assess if individual differences in the influences of haptic feedback existed.
- *Purdue Visualization of Rotations* (ROT) *Test*. Originally developed by Bodner and Guay (1977), this timed test assessed students' spatial ability, namely their ability to perform mental rotation tasks of 3-D objects. It was used as a covariant of student performance on the *Cell Exploration* pre- and post-assessments. The reliability of the 20-item version of this ROT test calculated the Kuder–Richardson 20 (KR-20) and/or split-half (SH) reliability coefficients, the KR-20 values between .80 and .92 suggest that the ROT test is internally consistent. The construct validity of the ROT test was established using the 30-item version as one of five measures of spatial ability in a study of the relative importance of cultural and neurophysiological factors in spatial test performance. The two most highly correlated spatial ability scores were on the ROT and Shepard–Metzler tests ($r = 0.61$, $p < 0.001$) (Bodner and Guay, 1997). This assessment is included in Appendix D.
- *Cell Exploration Pre-assessments* and *Post-assessments*. This is an eight item written-response instrument (Appendix B) that combines objective and open-ended questions designed to elicit students' knowledge about the structure and functioning of animal cells with particular attention given to the cell membrane selective permeability and the process of diffusion. The pretest and posttest items were

identical except for the order of the objective questions and the answer choices. The development of this instrument was informed by prior research that examined students' understandings of biological concepts, namely the 'cell' and 'diffusion.' It includes a diffusion Concept Evaluation Statement (CES) from Westbrook and Marek (1991) and an item from the Diffusion and Osmosis Diagnotic Test (DODT) developed by Dreyfus and Jungwirth (1988; 1989). A panel of science education experts and teachers reviewed these items for content validity and judged them to be scientifically and developmentally appropriate for the study. Results of pilot testing of instructional program with these assessments support its content validity. The reliability of these instruments was estimated by analyzing the multiple items measuring the same construct for consistency.

- *Haptic Assessment*. This performance assessment (Appendix E) was designed to evaluate students' ability to use haptic information to identify objects (cell parts) and compare which object attribute is most salient to the two groups in the study. During this assessment, students were asked to look at and feel a series of objects that varied according to properties such as compliance, viscosity, texture, and dimensionality (2-D or 3-D) and decide which object choice was most like the cell part they encountered during the instructional program. The content validity of this instrument was estimated by a panel of science educators.
- *Interview.* The interview protocol (Appendix E) included questions designed to gain insight into what aspects of the instructional program students found salient in regard to the availability of haptic feedback. This semi-structured protocol has face-validity and the student responses were used to support the quantitative data gathered.

- *Assessment of Instructional Module* (AIM). The AIM (Appendix C) is a self-report survey based on a similar instrument developed by Jones et al. (2003) designed to gather information about the affective impact of the haptic technology on the students' experiences. This instrument has been shown to have content validity in prior studies (Jones et al., 2003; 2004). This instrument's internal consistency was judged using a test of reliability (Cronbach's Alpha = 0.77).

Procedural Details

The research sequence (described below) describes an individual participant's involvement (see Figure 3.4).

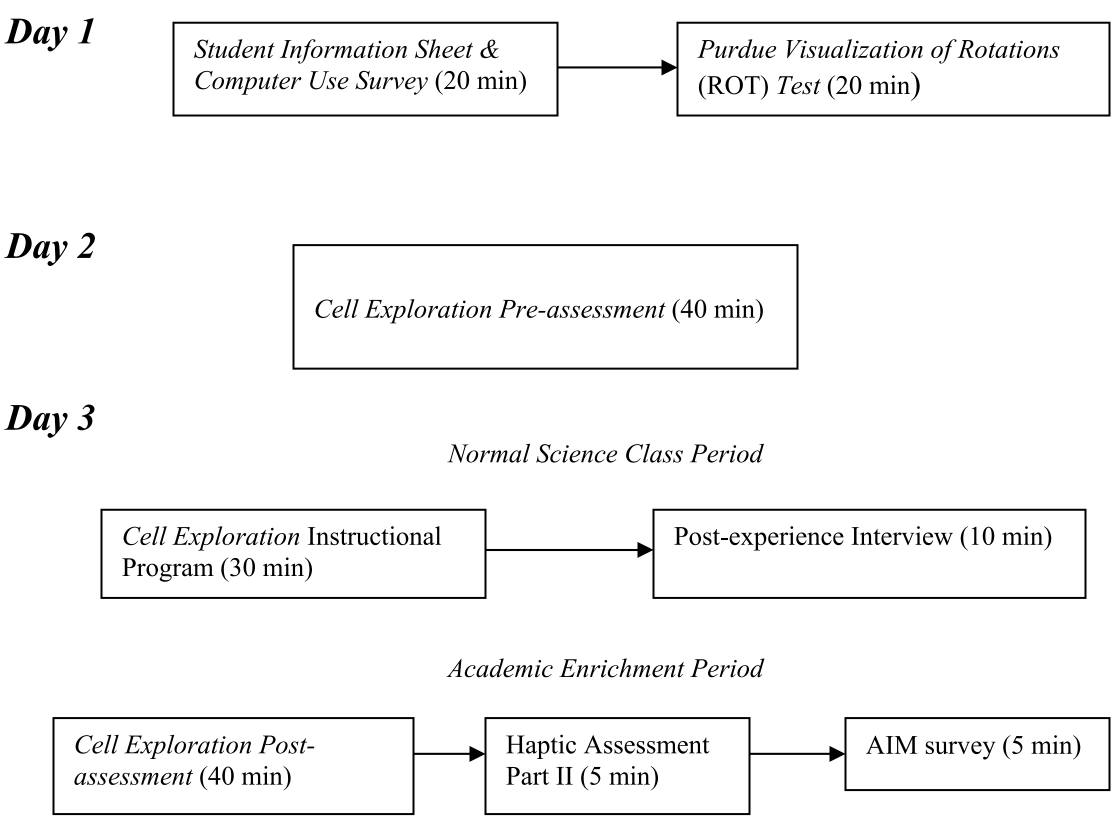

Figure 3.4. Sequence of events from the perspective of an individual student.

First, the student completed the *Student Information Sheet & Computer Use Survey* followed by the *Purdue Visualization of Rotations* (ROT) *Test* on day one of the study. The following day, the student completed the written *Cell Exploration Pre-assessment;* both of these days involved whole group assessments. On day 3 of the study, the student completed the instructional program, which was timed and controlled as indicated in the *Cell Exploration Guide* (Appendix A). Upon completion of the instructional program the student was interviewed by one of two researchers. Two "experimental stations" were employed to allow for 2 students per 4 class periods to complete the program and associated assessments on each day of the study.

During the last period of each day students returned to the study site and completed the *Cell Exploration Post-Assessment, Haptic Assessment, and Assessment of Instructional Module* (AIM) survey. Each participant spent a total of approximately 1.5 hours on this study.

The Cognitive Domain of Students' Learning

Research hypotheses and assessments.

Hypothesis: *Haptic feedback will impact students' ability to recognize and name the organelles found in a typical animal cell evidenced by significant differences in gain scores across treatment groups on the label the cell diagram item (p. 3, # 4- Cell Exploration Assessment).*

This objective selection assessment item asked students to examine a color diagram of the animal cell (a screen-shot from the instructional program) and choose the correct name for the part. Students were given one point for each correct response resulting in a total possible score of nine.

Hypothesis: *Haptic feedback will impact students' ability to correctly identify the corresponding functions of an animal cell's organelles evidenced by significant differences in gain scores across treatment groups on the match the cell part with its function item (p. 5, #6- Cell Exploration Assessment).*

This nine question objective (selection) item required students to match the name of the organelle with its function, as described in the instructional program. Students were given one point for each correct response, resulting in nine possible points.

Hypothesis: *Haptic feedback will impact students' knowledge of the process of diffusion as seen in significant differences by treatment in students' responses to the diffusion concept evaluation statement (CES) (p. 2, #3- Cell Exploration Assessment).*

This open-ended item presented students with a scenario: *A large 5 gallon glass container setting on a table is full of clear water. Several drops of dark blue dye are dropped on the surface of the water* … and asked them to explain what will happen to the blue dye. Student responses were scored using a rubric similar to the one used by Westbrook and Marek (1991). Students' written explanations of the process were given a number, ranging from 0 to 4, which corresponds with their "Level of Understanding" (from "No Understanding" to a "Scientifically Acceptable Understanding") as shown in Table 3.2.

Table 3.2

Evaluation Rubric for the Diffusion Concept Evaluation Statement (CES)

Score	Level of Understanding	Description	Example
4	Scientifically Acceptable Understanding	The student's response parallels a theoretical, abstract, scientific view of the concept of diffusion. None of the information contained in the response is incorrect.	*The dye is spread evenly to areas of low concentration from areas of high concentration. The process is called simple diffusion.*
3	Sound but Concrete Understanding	The student's response is complete, but not molecular in nature. The response is concrete rather than theoretical. No attempt is made to identify the molecular interactions. None of the information contained in the response is incorrect.	*I believe the process is simple diffusion. The blue dye will slowly go through the water dying it blue as it does so. This is an important part because diffusion is when one thing leaves one area (top of the water) and goes to another (bottom of container) without any help.*
2	Partial Understanding	The student's response contains part but not all of the above *scientifically acceptable understanding* or *sound understanding* criteria. The student's response contains some correct information, but may also indicate a misunderstanding about one or more aspects of the diffusion concept.	*The blue dye will mix with the water and turn the water blue.*
1	Alternative Conception	The student's response indicates a *complete misunderstanding* of the diffusion concept.	1) *The dye will sink to the bottom of the container. Contaminate the water so that it becomes a shade of blue. How dark or how light the color of the water will be based on how many drops of dye you put in the water.*
0	No Understanding	The student's response may include irrelevant remarks, a repeat of the question, or no attempt to answer the question.	*I don't know.*

Hypothesis: *Haptic feedback will impact students' descriptions of the molecular structure of the cell membrane indicated by significant differences in students' drawings (p. 6, #7- Cell Exploration Assessment) across the treatment groups.*

For this question, students were given the statement: *Suppose you could look deep inside a cell and see the structure (parts) of the* ***cell membrane****…what would it look like?* and instructed to draw and label the cell membrane in the space provided. Student drawings were assessed using a rubric that assigned one point for each appropriate characteristic of the cell membrane (i.e. the outer boundary of a cell or a bi-layer) and one point for a correct label.

The maximum score on this item was 10 points. Here a clear distinction was made between students' use of macro- or microscopic view of the cell membrane. This scoring rubric is presented in Table 3.3 below.

Table 3.3

Scoring Scheme for Students' Drawings of the Cell Membrane

Drawing Attribute	Part	Label	Points Earned
1) Macroscopic view of the cell membrane: **a)** Student drawing depicts a macroscopic view of the cell membrane with no reference to its molecular structure. Cell membrane is simply illustrated as the outer boundary.			
2) Microscopic view of the cell membrane: **a)** a bi-layer (lipid) illustrated			
b) phospholipids with 'head' and 'tail' regions included			
c) integral protein(s) included			
d) molecules or substances to be transported included			
e) substances depicted traversing the cell membrane.			
Total Points Earned out of 10:			

Hypothesis: *Haptic feedback will impact students' understandings of the mechanisms involved in passive transport and the cell membrane's selective permeability evidenced by significant differences across treatments in their analysis of a cell membrane-filter paper analogy (p. 4, #5-Cell Exploration Assessment) and explanation of 'selective permeability' (p. 6, #8-Cell Exploration Assessment).*

This open-ended item required students to reason by analogy and is presented as: *Another student states: "The passage of substances through the cell membrane is actually like the passage of substances through coffee filter paper." Do you think that this statement sounds correct?* Students' understandings of selective permeability were assessed using a rubric similar to the one previously described for the diffusion CES. Student responses were scored on a scale ranging from 0 to 5, with a 5 representing a thorough understanding of the mechanism behind the cell membrane's selective permeability, including all of the factors (i.e. size, shape, and chemical affinity of substances) that are the determinants for membrane permeability as shown in Table 3.4.

In addition, students' knowledge regarding this portion of the *cell concept* was evaluated using the following question: *The cell membrane is often described as a* ***selectively permeable barrier****. In your own words,* **explain** *how the cell membrane determines what gets in or out of the cell?* Again, this item was scored using a similar evaluation scheme (Table 3.5) with four possible "Levels of Understanding". A level four response included: a) selection criteria (size, shape, & charge) b) the role of integral proteins c) the phospholipid bilayer d) mentions specific examples of how substances traverse the membrane from the instructional program (oxygen, water, glucose, & potassium ions).

Table 3.4

Scoring Rubric for the Cell Membrane-Filter Paper Analogy

Score	Level of Understanding	Description	Example
5	Scientifically Acceptable Understanding	The student's response indicates a **thorough understanding** of the mechanism behind the cell membranes selective permeability. The student's response includes **ALL** of the factors- **size, shape, and chemical affinity (charge)** of substances that are determinants for membrane permeability. The coffee filter paper 'selects' according to size alone. None of the information contained in the response is incorrect.	*I think substances in a cell membrane make their way through due to their energy, size, & shape.*
4	Sound Understanding	The student's response indicates some understanding of the **mechanism** behind the cell membranes selective permeability. The student's response includes the **only one** of the following: **size, shape,** and **chemical affinity (charge)** of a substance as the basis for the cell membrane's permeability. The coffee filter paper 'selects' according to size alone. None of the information contained in the response is incorrect.	*Yes, I think this is correct because a coffee filter only lets things through that are small enough to go through. The cell membrane lets things in if they fit the shape of the protein of if they can fit between the little fish like things.*
3	Concrete Understanding	The student's response indicates an understanding that **both** the filter paper and cell membrane **are selectively permeable** in that they allow only certain substances to pass **but** makes **no reference to how substances are 'selected'**. None of the information contained in the response is incorrect.	*Yes, because some materials don't go through cells kinda of like some materials don't go through a coffee filter.*
2	Partial Understanding	The student's response indicates an understanding that **both** the coffee filter paper and the cell membrane are **permeable** in that they both only allow substances to pass through them **but** there is **no mention of any selectivity**. The student's response contains some correct information, but **may also indicate a misunderstanding** about one or more aspects of the concept.	*No because in a coffee filter the water mixes with the coffee and the coffee is left behind. The substances go through the cell membrane and nothing is left.*
1	Alternative Conception	The student's response indicates a **complete misunderstanding** of the concept.	1) *No, because the cell membrane tells the parts in the cell what to do.* 2) *No, because the endoplasmic reticulum keeps the bacteria from coming in only if it thinks its bad.*
0	No Understanding	The student's response may include irrelevant remarks, a repeat of the question, or no attempt to answer the question.	*I don't know.*

Table 3.5

Scoring Rubric for Student Explanations of 'Selective Permeability'

Score	Level of Understanding	Description	Example
4	Scientifically Acceptable Understanding	The student's response indicates a **thorough understanding** of ***how the cell membrane determines what gets in or out of the cell***. The response includes: **a)** selection criteria (size, shape, & charge) **b)** the role of integral proteins **c)** the phospholipid bilayer. **d)** mentions specific examples of how substances traverse the membrane from the instructional program (oxygen, water, glucose, & potassium ions). None of the information contained in the response is incorrect.	*Maybe the substances like the 'heads and tails' let water and oxygen molecules through but they didn't let glucose through. I think that 'protein' or something was used because the glucose molecule was too big to go through the 'heads and tails' so they got help from proteins.*
3	Sound Understanding	The student's response indicates a **general understanding** of ***how the cell membrane determines what gets in or out of the cell***. It describes some aspects of the membrane's selective permeability (determined by size, shape, and charge of substance) and recognizes a link between the membranes structure (proteins & phospholipids). The response **may not** make any references to substances from the program but none of the information contained in the response is incorrect.	*Cell membrane only allows skinny material to go through it like water and oxygen. It doesn't have that much space to let fat stuff through.*
2	Partial Understanding	The student's response contains some correct information from above categories, but **may also indicate a misunderstanding** about one or more aspects of the concept.	*1) A cell membrane rejects what it doesn't need.* *2) I think it determines what goes in and out cause if it does not want bad stuff in it, it will get its cell detectors to detect it out and if its not right they won't let it go through.*
1	Alternative Conception	The student's response indicates a **complete misunderstanding** of the concept.	*It means that's where the cell stores things like its memory or stuff like that.*
0	No Understanding	The student's response may include irrelevant remarks, a repeat of the question, or no attempt to answer the question.	*I don't know.*

Hypothesis: *Haptic feedback influences the way in which students select, organize, and integrate information about cell structure and functioning indicated by significant differences in the descriptions of cells (p. 1, #1-Cell Exploration Assessment) and the drawings of cells (p. 1, #2-Cell Exploration Assessment) across treatment groups.*

Two separate items generated information used to test this hypothesis, the first of which was: *In the space provided, tell me everything that you know about cells*. This free-response item was designed to provide insight into what content (from the instructional program) the students found salient and attended to (selected), as well as the manner in which this selected information was organized and integrated into their conceptions of a cell. To assess student responses on this item, *cell concept* content boundaries were established, essentially comprised of a series of scientifically acceptable propositional statements about cells (i.e. cells are microscopic and/or cells carry on the many functions needed to sustain life). Student responses were coded according to the above described framework illustrated in Table 3.6. One point was given for each acceptable statement; as a result students' total scores were bounded only by their scientific knowledge of the *cell concepts*.

The second item, from which information to test the above hypothesis was garnered, simply asked students *to draw and label a cell*. Students were given one point for each cell part (i.e. cell membrane, nucleus, mitochondria…) and one point for correctly labeling the part drawn resulting in 20 possible points. The rubric for this item is presented in Table 3.7.

Table 3.6

Content Boundaries Used to Assess Student Responses to 'Tell Me Everything That You Know About Cells'

***Cell Concept*-Content Boundaries**	**Example from student responses:**
a) Cells are the basic units of life.	*Cell is the smallest unit of organization.*
b) All living things are made of cells.	*Our body is made up of them. Cells are in your body!*
c) Cells are microscopic.	*Cells are little particles that you can not see.*
d) There exists great diversity in cell type.	*There are different kinds of cells that are in your body. It can be in plant & other animals.*
e) Some organisms are single cells; other organisms, including humans, are made of many cells.	*There are different types of cells.*
f) Cells carry on the many functions needed to sustain life.	*I know that we need them to live.*
g) Every cell is covered by a membrane that controls what can enter and leave the cell.	*The cell membrane monitors what comes in and out of a cell.*
h) Cells have specialized structures (organelles) that carry out such cell functions as energy production, transport of molecules, waste disposal, synthesis of new molecules, and the storage of genetic material.	*Cells are made up of different organelles. I know that the cell membrane is the outer part of a cell. Center of cell is called nucleus. It regulates activity in cell.*

Table 3.7

Scoring Scheme for 'Draw a Cell' Task

Drawing Attribute	**Part**	**Label**	**Points Earned**
a) cell membrane as outer boundary			
b) cytoplasm (internal space)			
c) nucleus			
d) mitochondria			
e) Golgi body			
f) ER			
g) vacuole			
h) lysosome			
i) ribosome			
j) genetic material			
Total Points Earned out of 20			

Two researchers independently scored 12 sets (pre- and posttest) of student responses chosen randomly from the sample. The researchers' scorings were compared with each other, disagreements were discussed, and the wording of the scoring rubrics was modified in order to best represent the raters' common understanding. Using the final versions of the rubrics, the mean inter-rater reliability for all six open-ended items was 94.3%.

Analyses. The initial step in the analysis of the cognitive assessment items was to check the normality of score distributions. This was done first with a visual assessment of a histogram of the frequencies of the pre- and posttest scores (for each item) and followed up with a Shapiro-Wilks test of normality. Next, using an analysis of variance (ANOVA) (two-tailed, alpha = .05), the pretest results on each item for the two groups were compared to see if the students' initial knowledge was similar. Subsequently, students' difference or gain scores (posttest score − pretest score) on each of the cognitive assessment items were calculated. The next step in the analysis involved the calculation of the pretest, posttest, and gain score means and standard deviations for each item. In order to determine if learning occurred, paired t-tests (two-tailed, alpha = .05) were used to see whether the means of the posttests were significantly different than those of the pretests on each item.

To investigate if significant differences existed between the two treatment groups a gain score approach was employed. The use of gain scores as a means of assessing the effectiveness of an instructional intervention is often criticized, perhaps incorrectly. The gain score approach is deemed by some to be quite reliable if pretest and posttest scores **do not** have equal variance and reliability (Dimitrov & Rumrill, 2003; Gliner, et al., 2003), which is true of all sets of scores in this study.

As part of the gain score analysis the use of an analysis of covariance (ANCOVA), (with pretest scores as the covariate), was explored. However, the necessary assumptions that there be a linear relationship between pretest and posttest scores and that the regression slopes of these scores must be homogeneous (have parallel regression lines) were not met. Ultimately, a 'simple' gain score approach was employed. Here mean gain scores on each item were compared using independent t-tests (two-tailed, alpha = .05).

To further investigate the influence of haptic feedback, two post hoc tests were conducted on the cognitive items. The first of which involved breaking the participants into three academic levels: high (n = 30), medium (n = 30), and low (n = 20). This classification was based upon groupings made by the two science teachers prior to the start of the study. To examine if haptics had a differential impact (due to academic level) on students' learnings, mean gain scores on each item were compared using independent t-tests (two-tailed, alpha = .05) across the two treatment groups for each of the three 'levels' of students individually.

The second post hoc analysis involved a closer inspection of the specific attributes (cell membrane, cytoplasm, nucleus, mitochondria, Golgi body, endoplasmic reticulum, vacuole, lysosome, ribosome, and genetic material) that students included in their drawings of the cell. The frequencies in which each of the various organelles were illustrated was tabulated and compared across the treatment groups. Using independent t-tests (two-tailed, alpha = .05).

The Affective Domain of Students' Learning

Hypothesis, assessment, and analysis.

Hypothesis: S*tudents who receive visual and haptic feedback will have more positive attitudes toward the instructional program when compared to students who receive only visual feedback (Assessment of Instructional Module (AIM)).*

This self-reported attitudinal survey included 20 Likert-scale items that elicited information regarding the affective impact of the instructional program. Students were asked to respond on a scale of 1 to 6 (1-*strongly disagree* to 6-*strongly agree*), to a series of statements about their level of interest, as well as the usability of the instructional program and associated interface. This questionnaire is included in Appendix C.

The data generated by this assessment are ordinal and Mann-Whitney U-tests were used to determine if significant attitudinal differences existed between the two treatment groups.

Differential Impact of the Instructional Program

Hypothesis: *There is a differential impact of the instructional program, with and without haptic feedback, according to students' gender, spatial ability, or amount of computer use outside of school (Student Information Sheet, Computer Use survey, and Purdue (ROT)).*

Information used to investigate this hypothesis was garnered from three primary sources (Appendix D). First demographic information was gathered on day one of the study; students also reported of the amount of time they spent using a computer outside of school as part of the *Computer Use Survey*. As part of the pre-experiment procedures students also completed the *Purdue Visualization of Rotations* (ROT) *Test* which is one measure of their spatial ability.

The differential impact of the instructional program, based on these three measures, was assessed statistically by including them in a multivariate general linear model in which the gain scores on the eight cognitive items served as the dependent variables.

Additional Sources of Data

Students' responses to the post-experience *Haptic Assessment* questionnaire (Appendix E) were used to further investigate the impact of the haptic feedback on their conceptions of the cell. The frequencies of student choices were tabulated and the proportions of student choices were compared across treatment groups using a Pearson's Chi-square test. This statistic is used to test the hypothesis of no association between columns and rows of nominal (categorical) data. A Pearson's Chi-square probability of .05 or less is ample justification for rejecting the null hypothesis that the row variable (treatment) is unrelated to the column (student choice) variable.

The semi-structured interview questions (see Appendix E) were designed to obtain information regarding the type of haptic information that students found or would find (in the case of comparison group) salient. Student responses were read multiple times by two researchers independently, patterns were discussed, and key points were used in support of the quantitative results.

Chapter Four

Results

Overview

The results of the study are organized according to the domains of learning discussed in the research hypotheses. The first section (*Establishing normality*) includes the results of the visual and statistical assessments of the pretest and posttest scores on the cognitive assessment items. The next section (*Students' initial knowledge*) presents results that show students in both treatment groups entered the study with similar understandings of the *cell concepts* and includes the results of the ANOVA of the pretest scores. The third part (*Did learning occur?*) compares the pretest and posttest scores for the entire sample. Section four (*Did haptics impact learning?*) provides results from the comparison of mean gain scores across the two treatment groups on the cognitive assessment items. The *Results by Hypothesis* section expands the presentation of these data. Finally, the results from the investigation into the impact that haptic feedback had on the *Affective Domain* of student learning, as well as the *Differential Impact* of this technology on students in the study are presented.

The Cognitive Domain of Students' Learning

Establishing normality. The initial step in the analyses of the eight cognitive items was to check the normality of pre- and posttest score distributions. Figure 4.1 includes some examples of the score histograms that were assessed visually for normality.

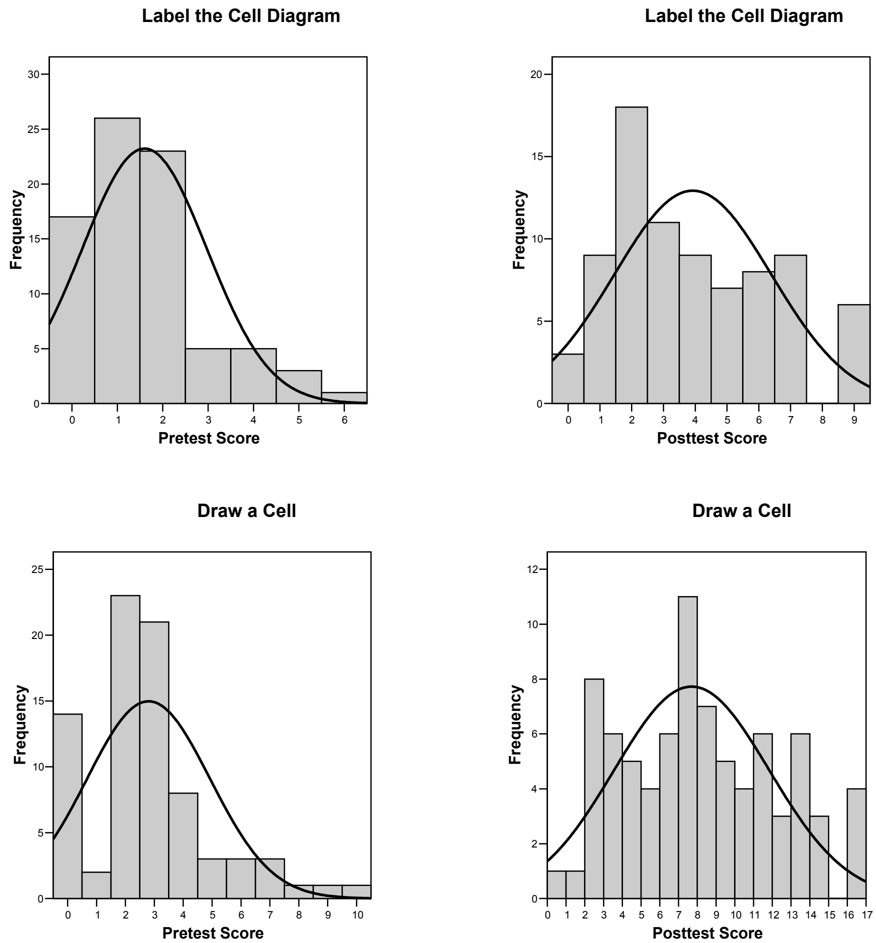

Figure 4.1. Representative examples (*Label the cell diagram* and *Draw and label a cell*) of score histograms used to visually assess normality. The left panels show pretest score distributions while the right panels show posttest score distributions.

The visual inspection of these graphs suggested that both the pretest and posttest scores on all cognitive eight items followed a relatively 'normal distribution.' The results of the Shapiro-Wilks test are shown in Table 4.1 and provide further support of score normality. This standard test of normality is essentially the correlation between the data points and their corresponding normal scores; a W statistic approaching 1 indicates a normal score distribution.

Table 4.1

Results of the Shapiro-Wilks W test of Normality for Cognitive Items

Assessment Item	Shapiro-Wilks W Statistic
Cell Diagram-Pretest	.869
Cell Diagram-Posttest	.930
Cell Organelle Matching-Pretest	.844
Cell Organelle Matching-Posttest	.891
Diffusion CES-Pretest	.785
Diffusion CES-Posttest	.858
Tell me everything that you know about cells-Pretest	.931
Tell me everything that you know about cells-Posttest	.868
Cell Membrane Analogy-Pretest	.823
Cell Membrane Analogy-Posttest	.907
Selectively permeable barrier-Pretest	.748
Selectively permeable barrier-Posttest	.890
Draw and label a cell-Pretest	.887
Draw and label a cell-Posttest	.968
Draw and label a cell membrane-Pre	.781
Draw and label a cell membrane-Post	.921

Students' initial knowledge. The students' pretest scores were compared, across the two treatment groups, on the eight cognitive assessment items using ANOVA tests (two-tailed, alpha = .05) to ensure that their initial knowledge regarding the *cell concepts* were similar (see Table 4.2).

Table 4.2

Analysis of Variance of Pretest Scores on the Cognitive Assessment Items

Source		*n*	*SS*	*df*	*MS*	*F*	*p*
Cell Diagram	Between Groups	80	2.45	1	2.45	1.30	.26
	Within Groups		146.75	78	1.88		
Cell Organelle Matching	Between Groups	80	1.51	1	1.51	.72	.40
	Within Groups		162.87	78	2.08		
Diffusion CES	Between Groups	80	.11	1	.11	.27	.60
	Within Groups		32.77	78	.42		
Tell me what you know about cells	Between Groups	80	3.61	1	3.61	1.08	.30
	Within Groups		262.07	78	3.36		
Cell Membrane Analogy	Between Groups	80	.000	1	.00	.00	1.00
	Within Groups		82.00	78	1.05		
Selectively permeable barrier	Between Groups	80	1.01	1	1.01	2.98	.09
	Within Groups		26.47	78	.33		
Draw and label a cell	Between Groups	80	.45	1	.45	.10	.76
	Within Groups		358.35	78	4.59		
Draw and label a cell membrane	Between Groups	80	.20	1	.20	.49	.49
	Within Groups		32.00	78	.41		

The results shown in Table 4.2 indicate that both groups of students entered the study with similar initial knowledge regarding the *cell concepts,* as evidenced by the lack of significant differences in their pretest scores on all eight cognitive items.

Did learning occur? In order to assess if 'learning occurred' during the course of the study paired t-tests (two-tailed, alpha = .05) were used to determine whether the means of the posttests were significantly different than those of the pretests on each cognitive assessment item. The results of this comparison are depicted in Table 4.3

Table 4.3

Comparison of Pretest and Posttest Scores for Entire Sample

	Pretest (n = 80)		Posttest (n = 80)				
Item	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*
Cell Diagram[a]	1.60	1.37	3.93	2.47	79	9.02	.000**
Cell Organelle Matching[b]	1.71	1.44	2.17	1.91	79	2.13	.036*
Diffusion CES[c]	1.84	.65	2.01	.77	79	2.56	.012*
Tell what you know about cells[d]	2.56	1.83	3.86	2.35	79	5.88	.000**
Cell Membrane Analogy[e]	1.00	1.02	2.41	1.12	79	11.75	.000**
Selectively permeable barrier[f]	.74	.59	1.86	.94	79	10.95	.000 **
Draw and label a cell[g]	2.80	2.13	7.70	4.13	79	11.61	.000**
Draw and label a cell membrane[h]	.85	.64	2.73	2.02	79	8.08	.000**

Note. Items were scored on varying scales.

[a,b]Items' maximum score was nine. [c]Item was scored using four levels. [d]Open-ended item's scores varied. [e]Item was scored using five levels. [f]Item was scored using four levels. [g]Item had a maximum score of 20. [h]Item had a maximum score of ten.

* $p < .05$, one-tailed. ** $p < .01$, one-tailed.

Table 4.3 reveals that there were significant differences in the students' pre- and posttest scores on all eight cognitive items, the magnitude and direction of these differences suggests that 'learning' did indeed occur.

Did haptics impact learning? To test for significant differences across treatment groups gain scores (on each item) were compared using independent t-tests (two-tailed, alpha = .05). The results of these comparisons are presented in Table 4.4 below. To aid in the reporting and interpretation of these data the results of the individual item's analysis is represented graphically and expounded upon briefly as it pertains to the specific research hypotheses of the study.

Table 4.4

Comparison of Mean Gain Scores Across Treatment Groups

	Visual Only (n = 40)		Visual + Haptic (n = 40)					95% CI	
Item	*M*	*SD*	*M*	*SD*	*Df*	*t*	*p*	Lower	Upper
Cell Diagram[a]	2.20	2.63	2.45	1.89	78	.49	.627	-1.27	.77
Cell Organelle Matching[b]	.60	1.78	.38	2.09	78	.52	.606	-.64	1.09
Diffusion CES[c]	.15	.70	.20	.52	78	.36	.717	-.32	.22
Tell me everything that you know about cells[d]	.98	1.92	1.68	2.01	78	1.60	.114	-1.57	.17
Cell Membrane Analogy[e]	1.33	1.12	1.53	1.01	78	.84	.404	-.67	.28
Selectively permeable barrier[f]	1.15	1.10	1.10	.71	78	.24	.810	-.36	.46
Draw and label a cell[g]	5.25	3.82	4.58	3.75	78	.80	.427	-1.01	2.36
Draw and label a cell membrane[h]	1.85	2.36	1.90	1.78	78	.11	.915	-.98	.88

Note. Items were scored on varying scales.

[a,b]Items' maximum score was nine. [c]Item was scored using four levels. [d]Open-ended item's scores varied. [e]Item was scored using five levels. [f]Item was scored using four levels. [g]Item had a maximum score of 20. [h]Item had a maximum score of ten.

* $p < .05$, one-tailed. ** $p < .01$, one-tailed.

Cognitive Results by Hypothesis

The first two research hypotheses predicted significant differences, between students who received visual and haptic feedback and those that received only visual feedback, in their ability to correctly identify cellular organelles and their corresponding functions.

Hypothesis: *Haptic feedback will impact students' ability to recognize and name the organelles found in a typical animal cell evidenced by significant differences in gain scores across treatment groups on the label the cell diagram.*

Hypothesis: *Haptic feedback will impact students' ability to correctly identify the corresponding functions of an animal cell's organelles evidenced by significant differences in gain scores across treatment groups on the match the cell part with its function item.*

The results depicted in Table 4.4 indicated that there were no significant differences between the two treatment groups' mean scores on the first two items. To further aid in the interpretation of the results, Figure 4.2 illustrates the mean scores on these two items.

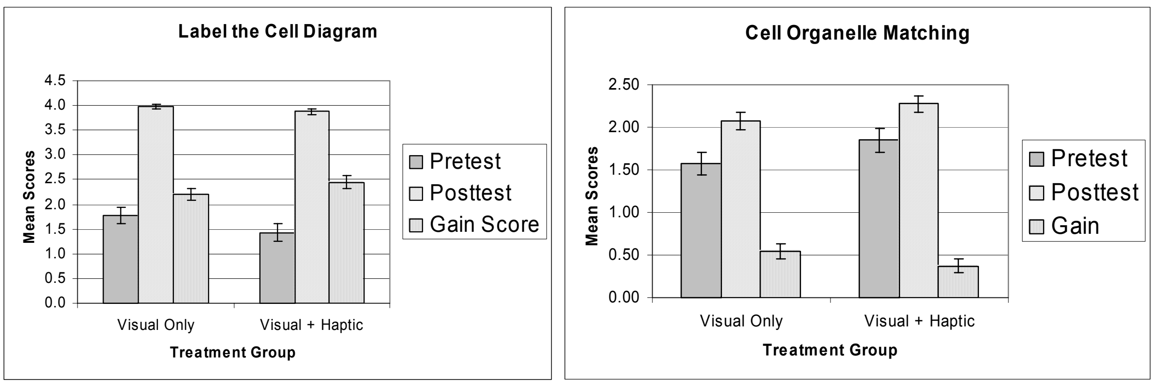

Figure 4.2. Comparison of mean pretest, posttest, and gain scores on objective items. The vertical lines depict standard errors of the means. The panel on the left represents the mean gain on the *Label the Cell Diagram* item. The right panel shows the mean gains on the matching task. Note that scale of the y-axes are different.

Hypothesis: *Haptic feedback will impact students' knowledge of the process of diffusion as seen in significant differences by treatment in students' responses to the diffusion CES.*

The *p*-value presented in Table 4.4 for the third assessment item indicates that addition of haptic feedback did not result in a significant difference in students' ability to provide a scientifically acceptable explanation of the process of diffusion. In fact both groups of students made minimal gains (Figure 4.3) in their level of understandings of the process, as evidenced by mean gain scores of 0.15 and 0.20 in the four- level scoring scheme used.

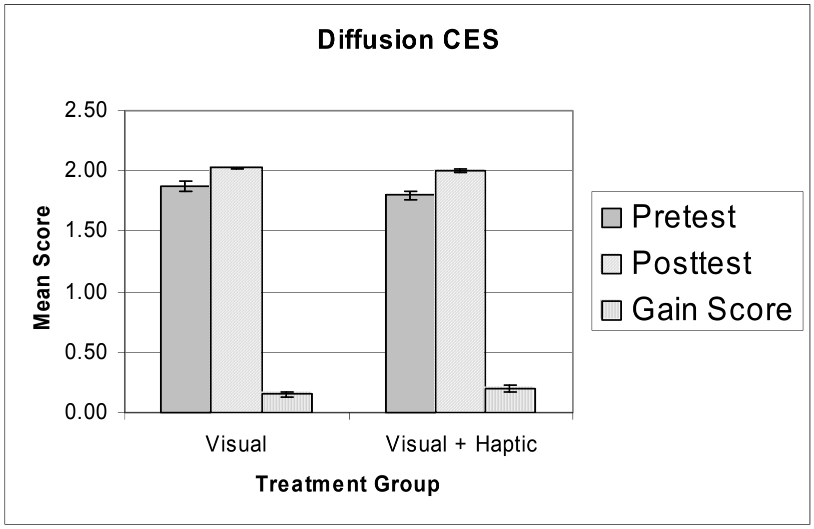

Figure 4.3. Comparison of mean pretest, posttest, and gain scores on the *Diffusion CES*. The vertical lines depict standard errors of the means.

Hypothesis: *Haptic feedback will impact students' descriptions of the molecular structure of the cell membrane indicated by significant differences in students' drawings across the treatment groups.*

The fourth research hypothesis predicted that haptic feedback would influence students' illustrations of the cell membrane resulting in significant differences in the groups' mean gain scores on the *Draw and label a cell membrane* task. An inspection of the results of the last assessment item from Table 4.4 and Figure 4.4 indicate that although both groups of students improved in their ability to accurately represent the cell membrane; the mean gain scores were not significantly different and were nearly equal in magnitude.

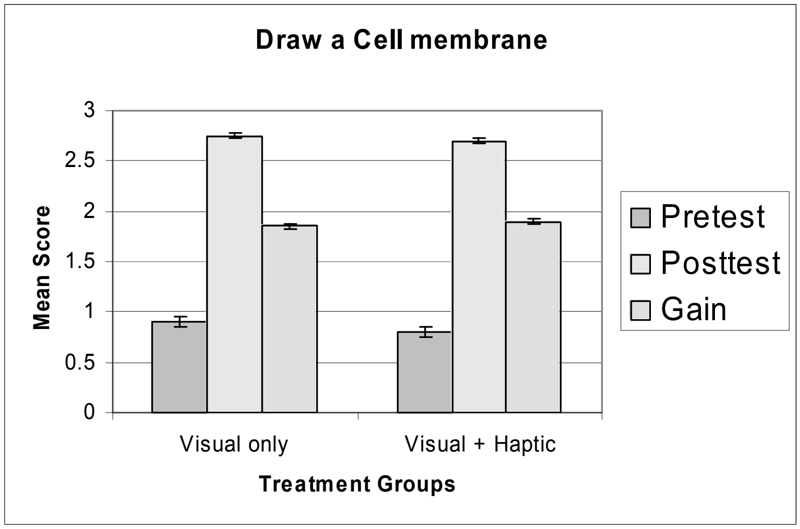

Figure 4.4. Mean pretest, posttest, and gain scores on the *Draw a Cell Membrane* task. The vertical lines depict standard errors of the means.

Hypothesis: *Haptic feedback will impact students' understandings of the mechanisms involved in passive transport and the cell membrane's selective permeability evidenced by significant differences across treatments in their analysis of a cell membrane-filter paper analogy and explanation of 'selective permeability'.*

This research hypothesis speculated that the addition of haptic feedback would enhance students' understandings of the processes and mechanisms involved in the cell membrane's selective permeability. Table 4.4, shows there are no significant differences across treatment groups in students' ability to accurately interpret the *Cell Membrane-Coffee Filter Analogy* or to describe how the membrane acts as a *selectively permeable barrier*. However, the mean gains (*Cell Membrane-Coffee Filter Analogy*: Visual-Only: M =1.33, Visual and Haptic: M = 1.53; *selectively permeable barrier*: Visual-Only: M = 1.15, Visual and Haptic: M =1.10) on these two open-ended items were relatively large given the nature of the leveled evaluation scheme used (Figure 4.5).

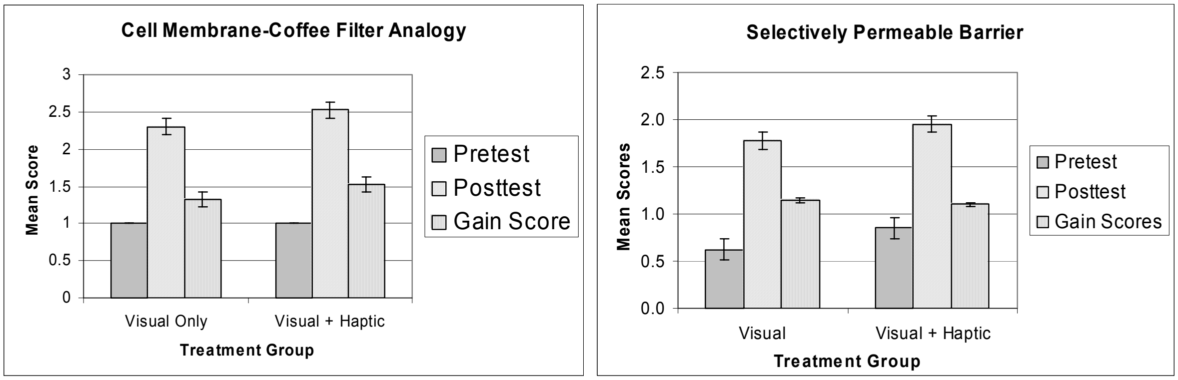

Figure 4.5. Comparison of mean scores on the cell membrane's mechanism items. The panel on the left represents the *Cell Membrane-Coffee Filter Analogy* and the right panel depicts the *selectively permeable barrier* question. The vertical lines depict standard errors of the means.

Hypothesis: *Haptic feedback influences the way in which students select, organize, and integrate information about cell structure and functioning indicated by significant differences in the descriptions of cells and the drawings of cells across treatment groups.*

The final research hypothesis examines whether there are significant differences between the two treatment groups in their selection, organization, and integration of information about the cell presented in the program. Although students from the visual and haptic feedback group had larger gains on average for the *Tell me everything that you know about cells* free-response item, the difference was not significantly different statistically (Figure 4.6).

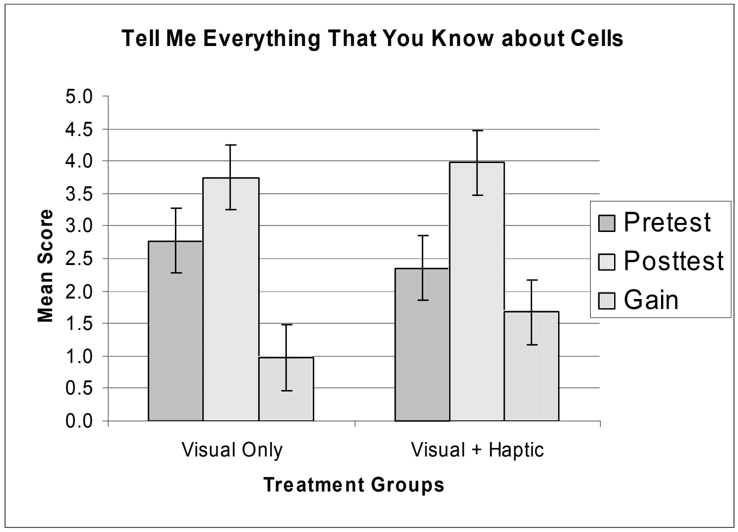

Figure 4.6. Mean pretest, posttest, and gain scores on the *Tell me everything that you know about cells* free-response item. The vertical lines depict standard errors of the means.

Figure 4.7 below shows that students who received only visual feedback had slightly larger average gain scores on the *Draw and label a cell* task.

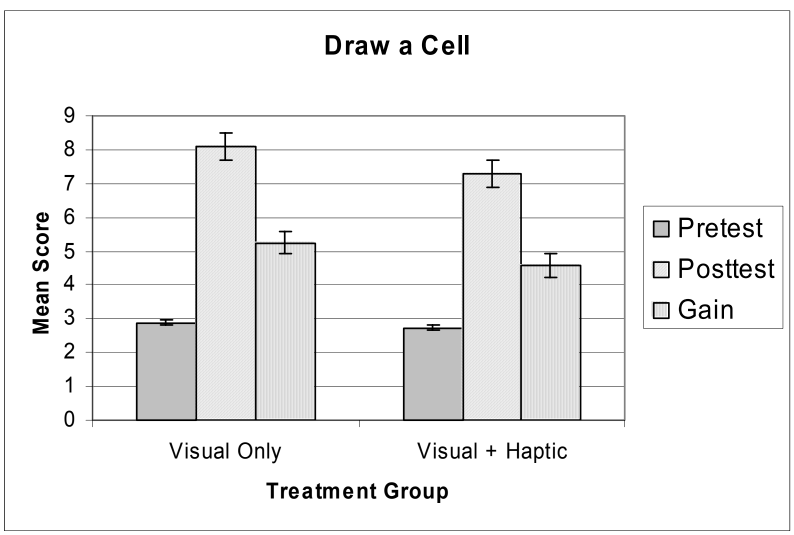

Figure 4.7. Comparison of mean scores on the *Draw and label a cell task*. The vertical lines depict standard errors of the means.

The results of the first post hoc analysis of the influence of haptic feedback on students' mean gain scores across the three academic levels (high, medium, and low) showed that there was a statistically significant difference on one of the eight items for one of the three levels of students (Table 4.5). In this case, the addition of the haptic feedback had a positive impact on the low-achieving students' ability to answer the question: *The passage of substances through the cell membrane is actually like the passage of substances through coffee filter paper. Do you think that this statement sounds correct? Please explain why or why not*.

Table 4.5

Significant Difference Across Treatment Groups for 'Low Level' Students

	Visual Only (n =14)		Visual + Haptic (n =16)					95% CI	
Item	*M*	*SD*	*M*	*SD*	*df*	*t*	*p*	Lower	Upper
Cell Membrane Analogy	.64	.76	1.44	.81	28	2.77	.010 *	-1.381	-.208

Note. Item was scored using a five level evaluation scheme.

* $p < .05$

The second post hoc analysis, involving the closer inspection of the specific attributes of the cell that students included in their drawings, showed no significant differences (independent t-tests; two-tailed, alpha = .05) between the groups in the frequency in which the various parts were illustrated.

Summary of the Cognitive Assessment Results

Viewed collectively, the analyses and findings of the cognitive assessment items suggest that although the addition of haptic feedback did not result in statistically significant learning differences, as measured by these assessments, overall the instructional program enhanced students' understandings of *cell concepts*. In particular there were relatively large mean gains in the students' ability to identify and correctly *label* the diagram of the cell, as well as in their capacity to accurately represent the structural components of a cell and its membrane. Moreover, marked improvements were made in the students' analysis of *the cell membrane-coffee filter paper analogy*. Only modest gains were made in regard to the students' ability to *match* the cellular organelles with its function and in their descriptions of the process of diffusion.

The Affective Domain of Students' Learning

Hypothesis: S*tudents who receive visual and haptic feedback will have more positive attitudes toward the instructional program when compared to students who receive only visual feedback (Assessment of Instructional Module (AIM))*.

The post-instruction *Assessment of the Instructional Module* (AIM) questionnaire was analyzed for differences in students' attitudes toward the instructional program. This instrument contained Likert-scale items that asked the students to report, among other things, their attitudes towards and interest level in the instructional program. Table 4.6 shows a comparison of student responses on these types of items.

Table 4.6

Comparison of Student Responses to AIM Interest Items

	Visual Only (n = 40)				Visual + Haptic (n = 40)					
Item	*M*	*SD*	*Mean Rank*	*Sum of Ranks*	*M*	*SD*	*Mean Rank*	*Sum of Ranks*	*U*	*p*
I believe that the graphics and animation enhanced the material presented in the program.[a]	5.20	1.18	39.3	1571.5	5.40	.84	41.7	1668.5	751.50	.600
I found using the PHANToM joystick to explore the cell interesting.[b]	5.63	.67	40.9	1634.5	5.58	.81	40.1	1605.5	785.50	.860
I am more interested in this topic after using the program.[c]	4.95	1.28	40.6	1625.5	4.93	1.27	40.4	1614.5	794.50	.955
I believe that I have learned a lot about cells by participating in this activity.[d]	5.13	1.22	40.2	1608.0	5.13	1.24	40.8	1632.0	788.00	.900
This program was different from the types of things we typically do in science class.[e]	5.08	1.47	35.3	1413.5	5.80	.46	45.6	1826.5	593.50	.013 *
On a scale of 1-10, with a 1 being not at all interesting and a 10 being extremely interesting, how would you rate this program?[f]	8.55	1.50	40.8	1632.0	8.45	1.71	40.2	1608.0	788.00	.905

Note: Responses to items a-e were on a 6-point Likert scale (1 = strongly disagree, 6 = strongly agree). The Mann-Whitney U test was used to compare treatment groups.
$*p < .05$.

Students from both treatment groups reported being quite interested in the program with mean ratings of 8.55 and 8.45 on a 10-point scale. Additionally, the responses of both groups of students suggested a high level of engagement. More specifically, they reported that the graphics/animations enhanced the material and that they found using the PHANToM interesting. Students' responses also conveyed that they felt as if they *learned a lot* about and were *more interested* in cells due to their participation in the study. There was a significant difference, $p = .013$, between students who received haptic feedback ($M = 5.80$, $SD = .46$) and those that did not ($M = 5.08$, $SD = 1.47$) for reports that the program was *different from the types of things they typically did in science class*.

The *AIM* instrument also contained questions that asked students to report on the usability of the instructional program and interface; Table 4.7 depicts these results. Overall, both groups reported similar attitudes towards the instructional program in terms of its ease of use (i.e. consistent and easy to follow directions, pace, and sequence). However, there were significant differences between the two groups regarding their level of frustration while using the PHANToM joystick ($p = .031$) and in their feelings of disorientation ($p = .003$). The students who received both visual and haptic feedback reported feeling less frustrated when exploring the cell ($M = 1.63$, $SD = 1.14$) than those students who relied only on visual feedback ($M = 2.33$, $SD = 1.59$) to conduct their investigations. This frustration may be due to the increased level of disorientation reported by the visual only group. When answering the question, *When exploring the cell, I often lost my spatial orientation (i.e. I wasn't certain where the point-probe was on the screen)*, students in the visual-only group tended to agree more ($M = 3.33$, $SD = 1.49$) than the students that received the bi-modal (visual and haptic) feedback ($M = 2.33$, $SD = 1.26$).

Table 4.7

Comparison of Student Responses to AIM Usability Items

	Visual Only (n = 40)				Visual + Haptic (n = 40)					
Item	*M*	*SD*	*Mean Rank*	*Sum of Ranks*	*M*	*SD*	*Mean Rank*	*Sum of Ranks*	*U*	*p*
I was able to recall & use information presented in the program following its use.	4.88	1.04	42.74	1709.5	4.60	1.23	38.26	1530.5	710.50	.369
The screen directions are consistent & easy to follow.	5.00	1.01	36.29	1451.5	5.33	.99	44.71	1788.5	631.50	.080
I was able to navigate through the program without difficulty.	4.28	1.15	38.23	1529.0	4.45	1.41	42.78	1711.0	709.00	.366
I felt that I was able to control pace and sequence of the program.	4.97	1.27	40.23	1609.0	5.13	.93	40.78	1631.0	789.00	.910
I found using the PHANToM joystick to explore the cell frustrating.	2.33	1.59	45.59	1823.5	1.63	1.14	35.41	1416.5	596.50	.031*
When exploring the cell, I often lost my spatial orientation (i.e. I wasn't certain where the pointer was on the screen).	3.33	1.49	48.11	1924.5	2.33	1.26	32.89	1315.5	495.50	.003**

Note: Responses were on a 6-point Likert scale (1 = strongly disagree, 6 = strongly agree).

The Mann-Whitney U test was used to compare treatment groups.

$^*p < .05$. $^{**}p < .01$

The Differential Impact of the Instructional Program

Hypothesis: *There is a differential impact of the instructional program, with and without haptic feedback, according to students' gender, spatial ability, or amount of computer use outside of school.*

The information gathered from the *Student Information Sheet & Computer Use Survey*, as well as the scores on the *Purdue Visualization of Rotations* (ROT) *Test* were used as covariates in a multivariate general linear model (GLM). This model was used to determine if the instructional program and its different feedback modes (visual-only vs. visual and haptic) had a differential impact on students' gain scores on the cognitive assessments (Table 4.8).

Table 4.8

Results of the General Linear Model for the Cognitive Assessment

Source	Dependent Variable	*SS*	*df*	*MS*	*F*	*p*
Treatment * Gender	Cell Diagram	43.06	1	43.06	8.63	.006 **
	Cell Organelle Matching	1.35	1	1.35	.331	.569
	Diffusion CES	.38	1	.38	1.05	.312
	Tell me everything that you know about cells	13.45	1	13.45	4.47	.042 *
	Cell Membrane-Coffee Filter Analogy	.06	1	.06	.05	.822
	Selectively permeable barrier	.01	1	.02	.01	.906
	Draw and label a cell	1.48	1	1.48	.08	.769
	Draw and label a cell membrane	1.61	1	1.62	.34	.562
Treatment * Comp.Use	Cell Diagram	32.96	4	8.24	1.65	.171
	Cell Organelle Matching	26.95	4	6.74	1.77	.144
	Diffusion CES	2.72	4	.68	1.92	.117
	Tell me everything that you know about cells	5.13	4	1.29	.32	.858
	Cell Membrane-Coffee Filter Analogy	13.75	4	3.44	3.39	.013 *
	Selectively permeable barrier	4.68	4	1.17	1.55	.197
	Draw and label a cell	31.52	4	7.88	.548	.701
	Draw and label a cell membrane	21.81	4	5.45	1.41	.238
Treatment * PVROT	Cell Diagram	39.19	10	3.92	.78	.642
	Cell Organelle Matching	21.70	10	2.17	.53	.856
	Diffusion CES	5.06	10	.51	1.37	.231
	Tell me everything that you know about cells	50.94	10	5.09	1.69	.122
	Cell Membrane-Coffee Filter Analogy	10.34	10	1.03	.88	.557
	Selectively permeable barrier	5.83	10	.58	.54	.847
	Draw and label a cell	136.48	10	13.64	.81	.624
	Draw and label a cell membrane	42.68	10	4.26	.90	.540

Table 4.8 *(continued).*

Source	Dependent Variable	*SS*	*df*	*MS*	*F*	*p*
Treatment * PVROT * Gender	Cell Diagram	35.70	4	8.92	1.79	.153
	Cell Organelle Matching	30.47	4	7.61	1.86	.139
	Diffusion CES	.90	4	.22	.61	.654
	Tell me everything that you know about cells	11.94	4	2.98	.99	.425
	Cell Membrane-Coffee Filter Analogy	2.20	4	.55	.47	.757
	Selectively permeable barrier	2.04	4	.51	.47	.753
	Draw and label a cell	51.71	4	12.92	.76	.556
	Draw and label a cell membrane	20.60	4	5.15	1.09	.376
Treatment * Comp.Use * Gender	Cell Diagram	7.91	3	2.63	.50	.680
	Cell Organelle Matching	25.12	3	8.37	2.50	.068
	Diffusion CES	.12	3	.04	.122	.947
	Tell me everything that you know about cells	3.60	3	1.20	.29	.827
	Cell Membrane-Coffee Filter Analogy	7.99	3	2.66	2.87	.064
	Selectively permeable barrier	.36	3	.12	.15	.924
	Draw and label a cell	5.66	3	1.88	.12	.947
	Draw and label a cell membrane	3.56	3	1.18	.29	.827
Treatment * PVROT * Comp.Use	Cell Diagram	1.57	2	.78	.11	.895
	Cell Organelle Matching	5.79	2	2.89	.57	.571
	Diffusion CES	.50	2	.25	1.54	.240
	Tell me everything that you know about cells	19.36	2	9.68	2.46	.113
	Cell Membrane-Coffee Filter Analogy	.42	2	.21	.16	.847
	Selectively permeable barrier	2.43	2	1.21	1.15	.337
	Draw and label a cell	10.63	2	5.31	.27	.763
	Draw and label a cell membrane	9.09	2	4.54	1.08	.358

Note. *p < .05. **p < .01.

Gender. There was a significant interaction between the treatment and gender on two of the cognitive assessment items (*Label the cell diagram* and *Tell me everything that you know about cells*). Males in the visual-only group had lower gain scores (n = 23, M = 1.78, SD = 2.59) on average than the females in this group (n = 17, M = 2.76, SD = 2.67) on the cell diagram labeling task. The opposite is true for the gain scores on the *Tell me everything that you know about cells* question. Here males in the visual-only group had significantly higher mean gain scores (M = 1.52, SD = 1.99) than their female counterparts (M = .24, SD = 1.56). There appeared to be no differential impact of the visual and haptic feedback by gender on these assessment items.

Computer use. There was also a significant interaction between the treatment group and computer use for the *Cell Membrane-Coffee Filter Analogy* question. On this assessment item the type of feedback seemed to have a differential impact for students that reported using a computer outside of school less than 1hour per week. For these low-level computer users, students in the visual-only treatment group had lower gain scores (n = 8, M = .75, SD = .89) than students that received both visual and haptic feedback (n = 9, M = 1.67, SD = 1.00). Conversely, higher-level computer users (4 to 6 hours per week) from the visual-only group had higher gain scores (n = 6, M = 2.50, SD = 1.05) than visual and haptic students (n = 4, M = 1.00, SD = 1.15) with the same amount of computer use. This same trend was seen in students who reported using a computer more than 6 hours per week on average. For these highest-level users, the visual-only group had higher gain scores (n = 4, M = 2.25, SD = 1.50) on the *Cell Membrane-Filter Paper* analogy question than the visual and haptic (n = 8, M = 1.38, SD = 1.06) high level computer user group.

Additional Data Source

Haptic assessment. The post-experience haptic assessment (Appendix E) asked students to make judgments, using both vision and touch, as to which object from a series of object choices was most like the cell, cytoplasm, mitochondria, and nucleus represented in the instructional program. Table 4.9 illustrates the object choices students were given. The accompanying graphs in Figure 4.8 illustrate the student choices across the treatment groups.

Table 4.9

Description of object choices from the Haptic Assessment

Feature from the Program	Object Choices
Cell	**1** = GREEN SPONGE BALL (SOFT) **2** = GREEN BALLOON * **3** = GREEN CIRCLE (2-D) **4** = GREEN STYROFOAM BALL (HARD)
Cytoplasm	**1** = GREEN DISH SOAP **2** = GREEN JELLO * **3** = GREEN WATER
Mitochondria	**1** = ORANGE PEANUT SHAPE (2-D) **2** = ORANGE *CIRCUS* PEANUT CANDY (SOFT) * **3** = ORANGE FOAM PEANUT (HARD)
Nucleus	**1** = RED GUMBALL (HARD) **2** = RED FOAM BALL (SOFT) * **3** = RED CIRCLE (2-D)

Note. * Denotes the choice that was deemed most valid by a panel of science educators.

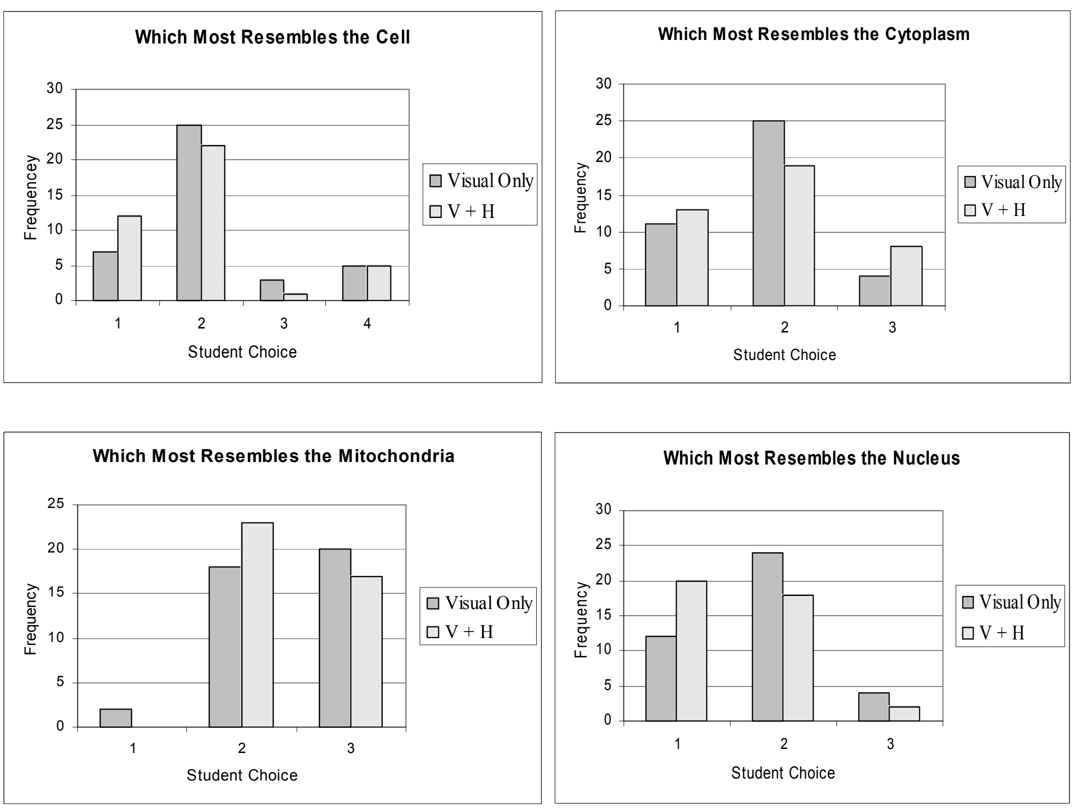

Figure 4.8. Frequency of student choices on the *Haptic Assessment* across the treatment groups. The numbers on the x-axes correspond to the object choices shown in Table 4.9.

Visual inspection of Figure 4.8 shows that although students were more likely to choose one object over the others (i.e. the balloon for the cell and the jello for the cytoplasm) there were no significant differences, by treatment, in their choices. The crosstabulation of the categorical data and Pearson Chi-squared analysis (Table 4.10) show there were no significant differences in students' object choices across treatment groups.

Table 4.10

Results of the Crosstabulation and Pearson Chi-Squared Analysis of the Haptic Assessment

		Choice				n	df	χ^2	p
Question	Treatment	**1**	**2**	**3**	**4**				
Cell	Visual Only	8	24	3	5	40	3	1.49	.683
	Visual + Haptic	11	23	1	5	40			
	Total	19	47	4	10				
Cytoplasm	Visual Only	12	24	4		40	2	1.67	.428
	Visual + Haptic	12	20	8		40			
	Total	24	44	12					
Mitochondria	Visual Only	2	18	20		40	2	2.85	.240
	Visual + Haptic	0	23	17		40			
	Total	2	41	37					
Nucleus	Visual Only	13	23	4		40	2	2.17	.337
	Visual + Haptic	19	19	2		40			
	Total	32	42	6					

Interviews. Student interviews (Appendix E) were conducted with the participants from both treatment groups immediately following their completion of the instructional program. Students from the 'experimental' group were asked directly about their haptic experiences, whereas students from 'control' group were prompted with hypothetical situations. For example students were asked: *Do you believe that being able to "feel" the organelles (parts) of the animal cell helped (would help) you learn about them? Why or Why not?* Only 12 out of the 80 students (15%) answered "no" to this question and of these 12 only 2 were students who had actually received the haptic feedback. Below are some sample responses to the above described interview question:

> It probably would. Feeling really stays in my head longer than visual (Visual-Only student).
>
> Oh yeah, that helped the most, looking you just get the shape. If you feel it, you can get specifics, smooth, or if it pokes you. Once you experience it, it is easier to remember than when you are just told like with a story (Visual and Haptic student).
>
> If I was feeling, I could feel the shape. I could figure out a word that starts with how it felt and I could remember it (Visual and Haptic student).

When asked about the features, qualities, or characteristics of the cell that they could "feel" the best (or would most want to be able to "feel"), the vast majority of the students named the nucleus, irregardless of their treatment group (44.8% for the visual-only group; 30% for the visual and haptic group). For example, students from the visual-only group said, "The nucleus; it looks like there is something in it. I want to know if it is hard or soft." and "The nucleus because it is the most important part; it is the brain of the cell. You can feel the little parts and know how each part worked in the nucleus."

Numerous students who had received haptic feedback suggested that they could "feel" the endoplasmic reticulum (ER) (22.5%) and Golgi body (20%) quite well. For example, "The ER because it has the little bumps; I could remember the ER had bumps because I could feel them" and "The Golgi body-you could tell it was stacks…layer by layer."

In responding to the question: *Do you believe that being able to "feel" the cell membrane helped (would have helped) you learn about its function (how it works)? Why or why not?*, 87.7% of the students (n = 80) suggested haptics did or would improve their understandings.

For example students' responded by stating:

> Yes, because if you can feel it you can learn how it opened or closed for certain things. Some things you just have to feel to learn even if it is 3-D (Visual-Only student).
>
> Yeah, because when you had the glucose pass through the heads it wouldn't let you but when you put it through the protein (channel) it took it away. You could feel the pull (Visual and Haptic student).

In summary, the results of the cognitive assessment items and the haptic assessment indicated that there were no statistically significant differences between the two treatment groups. Despite the lack of significance on these assessments, the responses to the post-experience interview questions suggest that students' felt as if the haptic feedback did or could enhance their understandings of the *cell concepts*. In addition, students from both groups reported having positive attitudes towards and high levels of interest in the instructional program. Finally, regarding the novel interface, significant differences were found between the two treatment groups; students who received haptic feedback reported feeling less frustrated and less disoriented during their exploration of the cell when compared to students who relied on visual feedback alone.

Chapter Five

Discussion

"Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise." (Tukey,1962, p. 58)

Overview

This chapter provides both theoretical and practical explanations of the observed results. More explicitly, the positive affective influences of the instructional program are discussed, followed by a detailed look at potential causes for the lack of cognitive gains observed. This section involves an examination of the nature and format of the instructional program itself, as well as the assessment techniques utilized. Here particular attention is given to the cognitive architecture and function of the students in an attempt to better understand their learning in a computer-mediated environment. The perception of object properties via the haptic sense and the implications of constraining haptic exploration with a point-probe are also discussed. Finally, ideas for future studies, born out of the results of the present one, will be shared.

The Affective Impact on Students' Learning

The results of the AIM analysis indicate that the computer-mediated *Cell Exploration* program had positive affective influences on the students in both groups. More specifically, participants from both conditions (visual-only and visual plus haptics) reported that they felt as if the graphics and use of the PHANToM joystick were highly engaging. Additionally, most students believed that they learned a lot about and were more interested in the topic of cells due to their participation in the study. The observed affective impact of this type of instruction is quite similar to that seen in earlier studies by Jones and her colleagues (2003;

2004). It has been suggested that involving students in consciously choosing to investigate the properties of an object is a powerful motivator and increases attention to learning (Sathian, 1998). While investigating the influence that haptic feedback (via a PHANToM device) had on middle and high school students' conceptions viruses, Jones and her associates (2003; 2004) found that students who received haptic feedback as part of microscopy experiments showed significantly better attitudes towards the instruction. In another study (Jones et al., 2004) comparing the impact of different feedback devices, similar affective results were observed. This experiment engaged students in a computer-mediated investigation of viruses and compared students across three treatment groups. One group used a mouse to conduct their investigations and consequently received only visual feedback. Another group used an inexpensive haptic gaming joystick and received rather crude tactile and kinesthetic feedback from stored atomic force microscope (AFM) images of viruses. The last group of students used the sophisticated PHANToM device to explore the virus images. The results of the study showed that students who received haptic feedback reported being more interested in and feeling as if they could participate more fully in the experience. Additionally, there were significant increases that corresponded with not only the availability of but also the fidelity of the haptic feedback in the number of affective terms (i.e. "This is cool" and "Awesome") used during student discourse; suggesting that the increased sensory feedback and stimulation made the experience more engaging and motivating to students.

In the present study, the student responses to the post-experience interview questions provide further evidence for these affective gains. When asked about the impact of being able to "touch" the cell and its parts, the vast majority of the students indicated that it did or would have helped them learn about these abstract concepts. For example students stated, “Yeah, because you could actually feel what it feels like, rather than just looking at it in a book and reading about it.” and “Being able to actually feel it helps. Yes, it helps me learn the different parts. I remember if it was squishy, round, or bumpy.”

Another interesting finding that emerged from the data regarding the affective influence of the technology were the significant differences found in the students’ self-perceived levels of frustration and disorientation. It appears that the addition of the haptic feedback aided in the students ability to navigate in the 3-D environment created in the program. These reports parallel the results of the seminal work done by Brooks and colleagues (1990) in which it was found that the addition of haptics radically improved the situational awareness of users engaged in computer simulated drug docking exercises. More recent and ongoing work by the Naval Aerospace Medical Research Laboratory involves the development and testing of a Tactile Situation Awareness System (TSAS) for providing accurate orientation information in land, sea, and aerospace environments (Naval Aerospace Medical Research Laboratory, 2000). This system helps to alleviate problems related to the spatial disorientation that often occurs when a pilot incorrectly perceives the attitude, altitude, or motion of his or her aircraft. It is believed that the integration of haptics (via a wearable vibrotactile transducer) with audio and visual displays leads to increased situational awareness.

Another growing area for the application of haptic technology is in surgical simulation and medical training scenarios (Tendick et al., 2000). Decreased levels of frustration coupled with increased spatial orientation and situational awareness result in benefits to both physician and patient. However, there are few accounts of any systematic testing and evaluation of these haptically augmented simulators (McLaughlin, Hespanha, & Sukhatme, 2002).

In short, the affective benefits of haptic technology have been demonstrated by several studies, including the present one. The addition of haptic feedback has been shown to have a positive impact on the users' interest in, attitudes towards, and ability to navigate in 3-D virtual environments. Notwithstanding these advantageous influences of haptics on the affect, the results of the present study depict a more modest cognitive impact.

The Cognitive Impact on Students' Learning

Viewed collectively, the *cognitive research hypotheses* of this study were formulated to evaluate the impact of haptic feedback on students' understandings of *cell concepts*. Borrowing from Mayer's (1996) SOI model, which provides a framework for investigating student cognition in computer-mediated environments, it was suspected that the addition of haptics would afford students the opportunity to become more fully immersed in the meaning-making process. It was postulated that the ability to "touch" and actively explore virtual models of the cell and its structural components would prompt students to *select* haptic clues and take advantage of tactile, kinesthetic, and experiential representations from memory. Furthermore, it was thought that students would *organize* this haptic information in a manner that could facilitate the building of referential connections between the names of cell parts and their representations, as well as associative links among cellular structures and their corresponding functions. In short, it was believed that haptics would promote a greater degree of *integration* and internalization of the salient aspects of the complex *cell concepts*. As a result, significant performance differences (evidenced by greater gains in knowledge) were expected for students receiving bi-modal (visual and haptic) feedback when compared to students that relied only on visual information. The results of the cognitive assessment items used in this study do not support these conjectures. One plausible explanation for these results is the unintentional limitations imposed by some of the assessments used in the study.

Assessment tasks. It is possible that the observed results may be due to the nature and format of the assessment tasks. It is reasonable to argue that the written paper and pencil cognitive assessment items did not access learning/performance differences that actually existed between the treatment groups. In essence, there may have been a mismatch between the mode of instruction and the 'test.' In retrospect, a more appropriate form of assessment may have involved the students, from both conditions, in the building of cell models with clay or other medium or in the haptic identification of cellular organelle models. These assessments, in combination with the more traditional written items employed may have made any cognitive differences that existed more evident.

Also implicated in this discussion of the assessment tasks are the evaluation schemes that were employed. Perhaps the strictly delineated scoring rubrics used to score the free response and open-ended cognitive assessment items did not adequately represent changes in students' understandings of the content. To illustrate this, Figures 5.1 and 5.2 show representative examples of students' (from the visual and haptic group) pre- and posttest drawings.

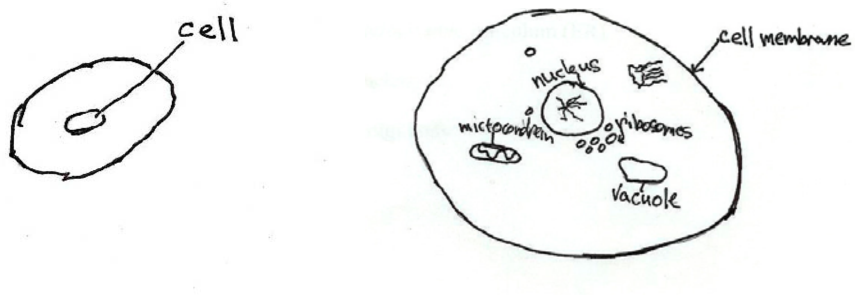

Figure 5.1. Example of one student's depictions of the cell. The left image shows the drawing from the pretest while the right side is the student's posttest representation.

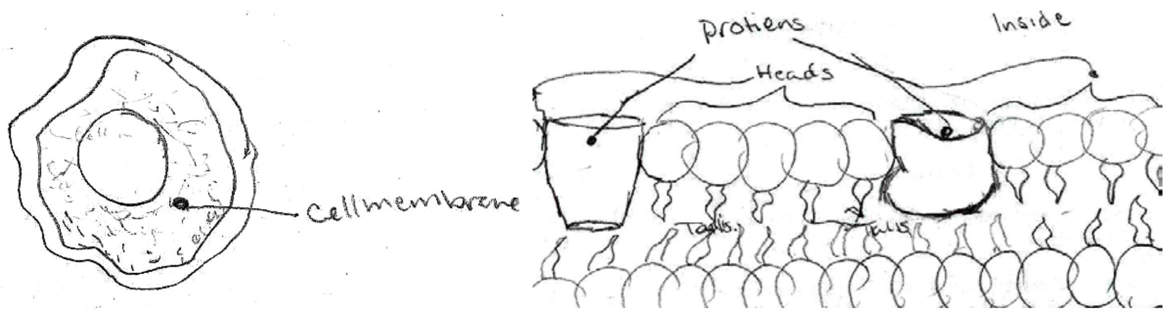

Figure 5.2. Example of a student's pretest (left) and posttest (right) drawings of the cell membrane.

These examples illustrate that there is a qualitative pre- to post-experience difference in the students' understanding and resulting depictions of the cell and its membrane, differences that may not have been captured by an evaluation scheme that simply assigned points for parts and labels. The same can be said of the rubrics used to score the students' written responses to the open-ended questions. Below is an example of a visual and haptic student's response to the question: *The cell membrane is often described as a selectively permeable barrier. In your own words, explain what this means. More specifically, how does* *the cell membrane determine what gets in or out of the cell? Be as specific as possible in your explanation.*

> Pretest: The substance goes through the cell membrane and analyze it by 'reading' what it is made of and filters it.
>
> Posttest: This means that the cell membrane only lets certain things in. Small things such as oxygen and water can get through the heads and tails. Large things like glucose must enter through a protein channel. Also positive charged substance must enter or exit through a protein channel.

Clearly, the above response suggests that the student's conceptualization of the cell membrane's selective permeability has changed. The pretest response lacks scientifically sound details and assigns anthropomorphic qualities (reading) to the membrane. This student's posttest answer indicates a thorough understanding of the process and even includes the criteria (size, shape, and chemical affinity) on which membrane permeability relies. In addition, the post-experience explanation includes specific substances (oxygen, water, and glucose) from the instructional program and makes clear connections between the structure (heads, tails, and protein channels) of the cell membrane and its function. According to the evaluation rubric (Table 3.5) the pretest response received a score of 2 and the posttest response was a scored a 4, resulting in a gain score of 2 that does not truly capture the nature of the cognitive impact of the instructional program on the student's understanding of this concept.

Cognitive architecture. When judging the efficacy of a computer-mediated program, such as the one utilized in this study, attention should also be given to the *cognitive architecture* (Sweller, van Merrienboer, & Paas, 1998) of the user and the limitations of the cognitive system in the processing of new information. More specifically, the natural limits of short-term memory, the manner in which information is organized in and retrieved from long-term memory, and the role that prior knowledge plays in the meaning making process must be considered. Collectively these factors can have a profound impact on the overall effectiveness of an instructional program.

Once stimuli, be it visual or haptic in nature, have entered one's sensory register it enters the working or short-term memory (STM). However, it is believed that STM is limited to about seven items or elements of information at any one time (Miller, 1956) and it is our STM that is used to organize, compare, contrast or 'work' on this information. As a result, individuals can probably only process two or three items of information simultaneously (as opposed to merely 'holding' larger amounts of information) (Baddeley, 1992).

Our long-term memory (LTM) is what we use to 'make meaning' of information we encounter and its contents and functioning are filtered through working or STM memory (Kirschner, 2002). It is thought that knowledge is stored in LTM as schemata (Chi, Glaser, & Rees, 1982) and schema construction is believed to aid the storage and organization of information in our long-term memory. A schema can be anything that has been 'learned' and it can hold a large amount of information which is processed as a single unit in working memory. As a result, schemata can help one to organize information elements (according to how they will be used) and may act to reduce the load on an individual's working memory.

The students' cognitive load. The cognitive load theory (CLT), put forth by Sweller in 1994, maintains that the memory load on a learner during a task is due to three interacting elements: *intrinsic*, *extraneous*, and/or *germane* loads. The *intrinsic* cognitive load is determined primarily by the inherent nature of subject matter presented in the instructional program. Conversely, an *extraneous* cognitive load is created by the way in which information is presented to learners and as a result can be managed through careful instructional design. A major assumption of cognitive load theory is that instruction should be structured to reduce unnecessary extraneous load on the user's already limited working memory (Pollock et al., 2002). The last type of cognitive load, *germane*, is also within the control of the instructional designer and refers to the mental cost of schema construction and storage in LTM (Sweller, van Merrienboer, & Paas, 1998). Ideally, instructional programs decrease the extraneous load but increase germane load on the learner.

The structure and functioning of this basic *cognitive architecture* suggests that instructional programs requiring learners to engage in complex processes involving combinations of unfamiliar elements are likely to present problems and may not work as well as expected (Kirschner, 2002). Learning, evidenced by performance change or 'gains' in knowledge (as is the case in this study), requires working-memory capacity. These ideas, explored further below, may be part of the explanation as to why the *Cell Exploration Program* employed in this study did not reach its full potential in the enhancement of students' conceptions regarding the cell.

Intrinsic load. First, it is suspected that the inherent intellectual complexity of the *cell concepts* covered in the instructional program used in the present study generated a high intrinsic cognitive load on the vast majority of the participants. Prior research has shown that students typically have difficulty comprehending that cells are autonomous organisms able to carry out the basic processes necessary for life, conceptualizing an accurate spatial representation of cells, and establishing the relationships between cellular structures and their functions (Flores and Tovar, 2003). The prior research also reveals conceptual difficulties regarding the abstract nature of the process of diffusion (Westbrook & Marek, 1991).

Moreover, the *cell concept* is high in 'element interactivity,' that is the material consists of elements that cannot be understood in isolation because they interact. For example, students may have been able to learn the names and perhaps even the function of individual parts of the cell membrane one at a time but they cannot understand how the cell membrane acts as a selectively permeable membrane without simultaneously considering these components and their relations. To exacerbate this already difficult and mentally taxing situation, it is suspected (based on their pretest scores) that the students in the study had very little in the way of existing schemata regarding the *cell concepts*. Students were challenged with a multitude of seemingly new and difficult vocabulary terms (i.e. names of cellular organelles and parts of the cell membrane) and abstract concepts (i.e. microscopic size, complex chemical processes of the cells, and diffusion). It is likely that without existing schemata to draw upon, attempts made by the students to assimilate and make meaning of all the elements of the *cell concept* were not successful due to working memory limitations.

Extraneous load. To compound the relatively high intrinsic cognitive load imparted on the students' working memory during this instructional activity, the design of the program itself may have added extraneous cognitive loads. First, students were expected to use a unique interface, the PHANToM, to conduct their investigations. Although all the participants were involved in a training session prior to the start of the study, it is reasonable to suspect that the novelty of this device in itself impacted their experience. Additionally, the duration of the intervention was brief; students were given approximately 30 minutes to complete the *Cell Exploration Program*. During this time students surveyed the internal structure of an animal cell (including the structure and function of its basic organelles), watched an animation about simple diffusion, and experimented with different substances to determine how they traverse the cell membrane. The content was verbally reviewed by the researcher and student upon the completion of each section but there was no 'scaffolding' built into the program. Perhaps students would have benefited from having to complete sequenced *simple-to-complex learning tasks* and completion tasks (van Merriënboer, Kirschner, & Kester, 2003). This would have prompted them to learn, practice, and apply more manageable 'chunks' of critical information. Additionally, the instructional program may have been more effective if it made use of *just-in-time information* presentation such as including timely presentation of information to support practice on learning tasks (i.e. pop-up windows that describe the size, shape, and chemical charge of the substances as students grabbed them) and the direct, step-by-step presentation of procedural information (van Merriënboer, Kirschner, & Kester, 2003). It is believed that any reduction in the extraneous cognitive load on the user would increase the germane load and result in more efficient schema construction during this complex learning task (Pollock et al., 2002).

Haptics and the Perception of Object Properties

Extensive research conducted by Lederman, Klatzky, and their colleagues (e.g., Lederman, 1983; Klatzky, Lederman, & Reed, 1987; Klatzky & Lederman, 2000) suggests that the haptic system is well-suited for the perception and subsequent encoding of the *material properties* of objects such as texture, hardness, compliance, elasticity, and viscosity. Conversely, they report that vision tends to dominate in the perception *geometric properties* like shape and size and color (Sathian et al., 1997; Verry, 1998; Klatzky and Lederman, 2000). Given this, it was hypothesized that students in the present study would instinctually use vision to extract information regarding the shape and relative size of the cell and its organelles, even when touch was available. It was also predicted that individuals from the haptic condition would find the *material properties* of the virtual objects particularly salient during their exploration. Thus features such as the flexibility of the cell membrane, viscosity of the cytoplasm, compliance of the nucleus, and texture of the rough endoplasmic reticulum would be readily *selected* by the visual and haptic students for further processing.

The absence of significant differences in the gain scores (between the two treatment groups) on the *Label the Cell*, *Cell Organelle Matching*, and two drawing tasks implies that the haptic sensations of the virtual objects' material properties provided during the instructional program were not as important to the students as anticipated.

Haptic exploration in the presence of vision. Much of the research investigating haptic perception has been conducted with subjects that have been deprived of vision, logically making haptic clues more vital. The circumstances created in the present study were quite different; individuals in the haptic condition received bi-modal feedback and could take advantage of both visual and haptic information as they progressed through the instructional program. This in itself may help explain why the expected performance gains (on the cognitive assessments) for the visual and haptic group were not observed.

Everyday perception is multisensory and it has become generally accepted that our visual and haptic perceptual systems are inextricably intertwined. However, the exact nature and functioning of this association is still under investigation. The results of a classic study by Rock and Victor (1964) focusing on the integration of visual and haptic information lead to the "visual capture" model. In this experiment subjects were asked to determine the perceived size of an object that they simultaneously saw and felt; however they were presented with an intentional conflict between their senses. More specifically, subjects looked at the object through a cylinder lens that caused a square to look like a rectangle which created a conflict between visual and haptic information. It was found that vision dominated the integrated precept whether subjects reported perceived size by drawing, visual matching or haptic matching, hence leading to the idea of "visual capture."

Klatzky, Lederman, and Matula (1991) raised this issue of 'modality specificity in perceptual encoding' and described this as the differential appropriateness of visual and haptic information. They suggest that when vision is available and adequate for a task, haptic exploration may not be evoked due to its relatively high processing cost. Additionally, the visual recognition of an object may rapidly trigger the retrieval of information about its properties stored in memory that are semantically accessible; thus eliminating the need for direct perceptual encoding by vision or haptic exploration (Klatzky, Lederman, & Matula, 1993).

With this in mind, it is suspected that students in this study identified objects (i.e. cellular organelles and membrane parts) based primarily on visual information. Even though the material properties (i.e. texture, compliance, elasticity, and viscosity) of various organelles were modeled and available (for perception and processing) to the students in the visual and haptic condition, they may have relied heavily on the objects' size, shape, and color (geometric properties) to make their discriminations and decisions. Klatzky, Lederman, and Matula (1993) proposed two serial models for the initiation of haptic exploration that support and build on the idea of the "visual capture" of object properties and the above suppositions made regarding the results of the present study. The *Visual Dominance* and the

Visual Preview models (Figure 5.3) both maintain that haptics defers to vision; that is, haptic exploration is employed only after initial visual analysis.

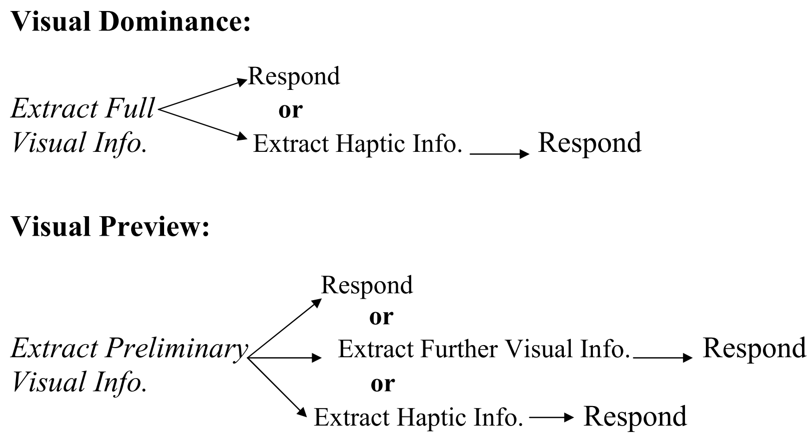

Figure 5.3. Klatzky, Lederman, and Matula’s (1993) models representing the haptic exploration of objects in the presence of vision.

According to the *Visual Dominance* model (Figure 5.3), visual analysis is exhausted before any haptic exploration is initiated. In other words, if enough information is gained through vision alone, the object is not ever “touched.” The *Visual Preview* model includes a brief visual analysis resulting in a response if adequate information is obtained. If more information is needed, the individual may extract additional information visually or begin haptic exploration. Considering these models and the fact that students are traditionally presented information and concepts using visual stimuli alone, one can reasonably conclude that the additional perceptual information made available through haptic exploration was never fully capitalized on by the students in this study.

Sensory Integration. A few more recent studies depict a far different story and have shown a clear influence of haptics on vision, demonstrating that vision does not necessarily completely ‘capture’ haptics (Ernst & Banks, 2001; 2002). This work has begun to help ‘untangle’ the way in which humans achieve robust perception through the combination and integration of information from multiple sensory modalities. In a haptic-alone experiment, observers indicated which of two sequentially presented ridges was taller from haptic information alone; in a visual-alone experiment, they did the same from visual information alone. Ernst and Banks (2001) determined the reliabilities for discriminating sizes for each modality alone to make predictions for the weights and the integrated reliability in a cross-modal or bi-modal case. There were four conditions in the visual experiment that differed in the amount of noise (random displacement of the dot depths) that was on the display. These varying degrees of noise allowed the researchers to manipulate the reliability of the visual stimulus and thus the weight changed from visual dominance (when there was no noise added to the visual display and the visual information was very reliable) to haptic dominance when there was a lot of added noise. In essence, the subjects’ behavior went from a ‘visual capture’ to ‘haptic capture’ model of processing. These studies have shown that humans combine visual and haptic information about object size in a way that approaches statistical optimality. Moreover, the cross-modal or bi-modal discrimination thresholds were always smaller than the individual visual and haptic thresholds, suggesting sensory fusion (Ernst & Bülthoff, 2004).

These performance indicators, in concert with neuroimaging studies (Zangaladze et al., 1999; Amedi et al., 2001) that have yielded functional magnetic resonance (fMRI) images of occipital cortex activation during both visual and haptic object recognition tasks, suggest that sensory integration is indeed occurring. The observed overlap in the neural structures involved in visual and haptic processing of object properties implies that the haptic system may exploit the well developed object representation systems of the ventral visual pathway but a definitive answer as to the precisely how haptic information is organized and integrated in the brain still eludes us.

Point-probe exploration in a virtual environment. There are numerous everyday situations that require us to be proficient at identifying objects with our bare hands, even without the aid of vision. For example, we often reach into our pockets stuffed with visually occluded objects to successfully remove a set of keys or grab a cup off the nightstand in a dark bedroom without spilling its contents (Klatzky, Lederman, & Metzger,1985). In such unconstrained haptic explorations, a bevy of tactile and kinesthetic inputs are available for further processing. However, our haptic perception is impaired considerably when manual exploration is constrained. Such a constraint existed in the present study in which students were expected to remotely explore a set of unfamiliar objects using the rigid point-probe of the PHANToM. Overall, perception and subsequent performance in a virtual environment (such as the one created for the *Cell Exploration* instructional program) is degraded from that possible in live environments. This degradation is due primarily to a substantial decrease in the number and size of contact areas between the user and the object caused by the point-probe itself, as well as the approximations inherent in the computer models of simulated contact. For example, using the *contour following* EP (see Figure 2.2) to obtain shape information would be particularly difficult and inefficient using a single point of contact.

Such perceptual costs of constraining haptic exploration to a single point were recently demonstrated in a study by Lederman and Klatzky (2004) in which response times increased considerably (by a factor of 4 relative to a bare-finger condition) with the use of a rigid probe of a PHANToM. Presumably, such constraints limited students' access to precise textural and geometric details. Specific to the present study, the constrained point-probe exploration required the sequential tracking of the cellular components' contours and spatial patterns. This necessity likely imposed an additional memory load and may have limited the effective temporal integration of those inputs related to the objects' overall 3-D structure (Lederman & Klatzky, 2004).

Future Work and Implications on Science Instruction

Aside from the recommendations for improvement alluded to throughout the earlier portions of this discussion, there are several other studies that may lead to significant contributions to the growing research base on haptics. First, is a study that controls for the level of 'user interactivity' in this type of computer-based learning environment and that incorporates three treatment groups. One treatment that passively views the *cell concepts* science content (perhaps via a slideshow), one group that interacts with the *Cell Exploration* 3-D environment using a PHANToM but receives only visual feedback, and a third condition that uses the PHANToM to garner both visual and haptic information from the instructional program. Comparing the affective and cognitive impact of the instruction across these groups may help pin-point the role that 'student interactivity' in itself plays this type of instruction.

Given the earlier argument that students in this study were not able to fully capitalize (due in part to lack of experience) on the additional kinesthetic and tactile sensations provided by the haptic interface, it might be fruitful to explore the impact of extended PHANToM use. More specifically, assessing the influence that practice or training in the use a point-probe device has on the quantity and quality of haptic information that individuals' select and attend to. Additionally, a study of the effects that prolonged use has on the way in which this selected haptic information is organized and integrated seems warranted.

Perhaps, through practice alone, students' implicit memories of the haptic tasks and the associated sensory feedback would improve; essentially leading to a higher degree of "perceptual fluency." Consequently, it may be observed that through this *priming* (Srinivas, Greene, & Easton, 1997) students become better able to tap into their embodied non-propositional knowledge (Reiner, 1999) and build more and stronger *associative connections* among existing images and prior knowledge, helping students create more connected experiential meanings of complex objects and events.

Several other ideas for future studies revolve around the development and subsequent evaluation of the impact of haptic feedback in a variety of new learning contexts. More precisely, it would be both interesting and informative to investigate the cognitive and affective impacts of incorporating this innovative technology in a variety of 'haptically rich' learning environments. For example, the study of physics students in a virtual environment engaging in 'hands-on' experiences with invisible forces such as gravity and friction at the macro- and microscale or an investigation of how having middle school students experiment with work, force, and motion using a PHANToM influences their understandings of these abstract concepts would likely result in valuable contributions to the research base in this area. Additionally, a study exploring how chemistry instruction, involving the 'feeling' of the attractive and repulsive forces associated with various compounds and molecules, enhances students' conceptions would certainly add to our understanding of this mode of instruction. Advances in this technology may open the door for students to potentially use haptic augmented virtual reality to learn more fully about the solar system and the effects of gravity on different planets. In the near future visually-impaired students may learn mathematics by touching data represented in a tangible graph.

The full potential of this technology may not be realized until more exploratory research into how students perceive, process, store, and make use of haptic information in a variety of educational contexts and settings are conducted. There is a critical need for more studies actually conducted in schools that pay attention to developmental, cognitive, behavioral, social and cultural factors that contribute to the complex milieu of today's classrooms and ultimately determine the efficacy of this technology. In turn, informed by this present study and future work in this area, this prospective new instructional tool can have direct implications on the way in which school science in taught.

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APPENDIX A

CELL EXPLORATION GUIDE

CELL EXPLORATION Guide

This document serves as a template for the researcher as he/she guides the student through the instructional program. Its intent is to highlight the essential information that all students should attend to and is formatted as a script. Tell students to ignore the parts referring to the 'Student Notebook'.

[suggested answers with key concept(s) underlined] (notes to researcher)

Part I: The Animal Cell & its Organelles

A) Exploration:

Researcher: *You will have* ***10 minutes*** *to complete this part. You can spend some time exploring first but remember you will need to gather information on all the parts of the cell represented. Be sure to read the text that appears in the upper left of your screen. Please let me know when you have finished.* (Allow student to explore; "R" key resets image; red fingertip is the contact point.)

B) Review:

Researcher: *Use the point-probe to identify and briefly explain the function of each of the cell parts shown in the model* (listed below; order not essential):

Cell membrane [It controls the movement of materials into & out of the cell.]

Cytoplasm [refers to everything between the cell membrane and the nucleus. It consists of primarily of water but it also contains various organelles as well as salts, dissolved gasses and nutrients.]

Nucleus [It directs all cell activity.]

Genetic Material [The tangled strands inside the nucleus that store the information needed for the cell to function.]

Mitochondrion [the site of cellular respiration that provides energy for the cell. The folded inner membrane increases the surface area where the energy production occurs.]

Golgi body [a series of stacked membranes that package proteins for the cell.]

Lysosome [small sacs that contains powerful digestive enzymes that help protect the cell by engulfing and ridding the cell of "foreign invaders" like bacteria.]

Vacuole [act like "storage tanks" for the cell and may contain or store food, waste or water.]

Endoplasmic reticulum (rough) [is a series of double membranes that fold back and forth. The rough E.R. has ribosomes attached to it. The ER helps move substance through out the cell.]

Ribosomes [manufacture or make proteins for the cell.]

(Note: Re-direct students to correct information if incorrect responses are given.)

Part II: Passive Transport

A) Viewing:

Researcher: *Next you will watch a* ***4 minute*** *animation about passive transport. Following the animation I will ask you several questions about what you saw.*
(When animation appears, maximize it. After it shows: "This concludes our animation of Facilitated Diffusion" close it twice and click next.)

B) Review:

Researcher: *Passive transport is the movement of molecules across the cell that:*
a) requires energy *[b) does not require energy]*

Researcher: *Can you name two (2) types of passive transport?*
[diffusion, osmosis, & facilitated diffusion]

Researcher: *Fill in the blanks. Diffusion is the movement of molecules from an area of ___________________ concentration to an area of ______________________ concentration.*
[high; low]

Researcher: *When does* d*iffusion end?*
[when the amounts are equal on both sides – equilibrium is reached]

Researcher: *If a molecule can not pass through the cell membrane sometimes a ______________________ may help or assist the molecule across.*
[protein]

(Note: Correct students if incorrect responses are given.)

Part III: The Cell Membrane

A) Exploration:

Researcher: *In this section you will have the opportunity to get a close-up view of the cell membrane's structure and explore its parts. You will have* ***5 minutes*** *for this section.*

B) Review:

Researcher: *Describe the phospholipids that make up the cell membrane*. (Prompt if needed: What are the two parts that make up the phospholipids?)

> [the molecules that make up the bi-layer of the cell membrane; have a hydrophilic "head" and a hydrophobic "tail" region.]

Researcher: *How do the heads and tails of these phospholipids differ?*

> ["Heads" are hydrophilic which means "water-loving"; these substances are attracted to water. "Tails" are hydrophobic which means "water fearing"; these substances are not attracted to water.]

(Note: Correct & re-direct students if incorrect responses are given.)

Part IV: Passive Transport

A) Exploration:

Researcher: *Finally, you are able to investigate how certain materials can pass into and out of the cell. Follow the on-screen directions, your goal is to grab the molecules and pass them through the cell membrane until equilibrium is reached. You will have* ***10 minutes*** *for this section*. (Allow students to play.)

Researcher: N*ame some of substances that may need to pass through the cell membrane.*

> [glucose (sugar), oxygen, water, & potassium ions]

Researcher: *Why did some molecules pass through the center of the cell membrane (the phospholipids) and others did not?*

> [glucose is too large to pass through the bi-lipid portion membrane so it uses protein channels to help (facilitate) its transport; oxygen is gaseous, small, & non-polar so it can easily pass through the bi-lipid layer; water is polar but small enough (we think) to pass through the bi-lipid layer; potassium ions are small but charged and can not pass through the bi-lipid layer & need to pass through a protein channel which creates a water-filled cavity that allows the charges particle to pass through.]

> [In short we want students to begin to understand that the cell membrane is selectively permeable in that certain molecules can pass in/out of cell based on the substances: size, shape, and/or chemical affinity.]

APPENDIX B

COGNITIVE ASSESSMENT INSTRUMENTS

Name:____________________________________ ID:_____________
Date:____________________________ Period:___________________________
Treatment (Leave blank):___________________

Cell Exploration-Pretest

1) In the space provided, *tell me everything that you know* about **cells**.

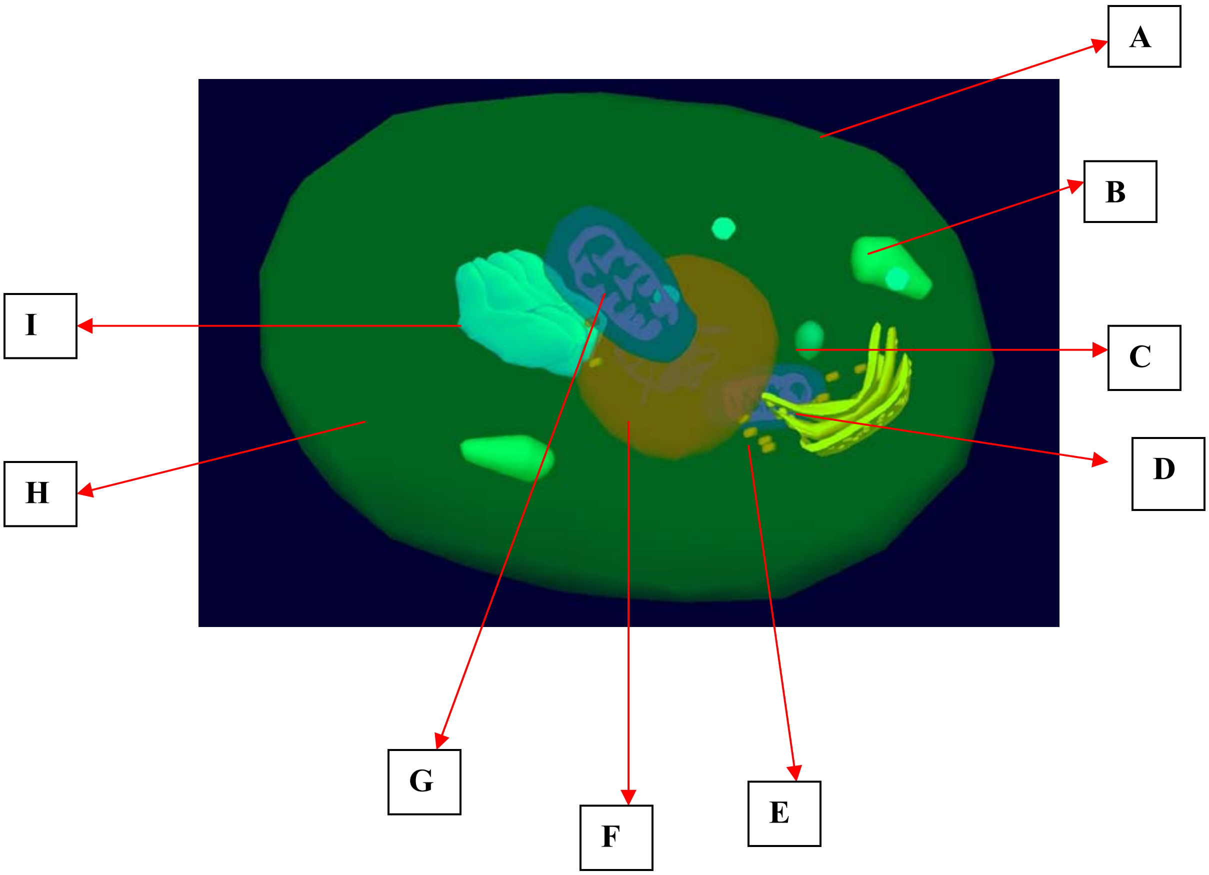
2) In the box, please draw and label a **cell**.

3) A large 5 gallon glass container setting on a table is full of clear water. Several drops of dark blue dye are dropped on the surface of the water. In a paragraph, **explain** what will happen to the blue dye. **Be sure to write down any specific details about the process. Name the process.**

Name:____ ID:______________
Date:______________________________ Period:___________________
Treatment (Leave blank):_________________

Cell Exploration-Pretest

4) Examine the color illustration of a typical animal cell on the separate page. Match the labeled cell parts with the correct name for that part. Place the letter on the line next to the name.



Cell Parts:

____ lysosome ____ cell membrane

____ mitochondrion ____ endoplasmic reticulum (ER)

____ cytoplasm ____ nucleus

____ vacuole ____ Golgi body

____ ribosomes

5) Another student states: “The passage of substances through the cell membrane is actually like the passage of substances through coffee filter paper.”

Do you think that this statement sounds correct?

Please explain why or why not.

Name:________________________________ ID:____________
Date:_________________________ Period:______________
Treatment (leave blank):___________________

Cell Exploration-Pretest

6) Match the description of the cell part on the left with the correct name for that part & put the letter on the line.

Description	**Name of Part**
____ 1) controls the movement of materials into & out of the cell	**A)** lysosome
____ 2) directs all cell activity & contains genetic material that stores the information needed for the cell to function	**B)** cytoplasm
____ 3) the site of cellular respiration that provides energy for the cell	**C)** cell membrane
____ 4) a series of double membranes that helps move substances throughout the cell	**D)** ribosomes
____ 5) manufacture or make proteins for the cell	**E)** vacuole
____ 6) small sacs that contain powerful digestive enzymes; they help protect the cell by ridding it of "foreign invaders"	**F)** nucleus
	G) endoplasmic reticulum
____ 7) packages proteins for the cell	
____ 8) act like storage tanks for the cell and may contain or store food, waste or water	**H)** mitochondrion
____ 9) everything between the cell membrane and the nucleus; it consists of primarily of water but it also contains various organelles as well as salts, dissolved gasses and nutrients	**I)** Golgi body

7) Suppose you could look deep inside a cell and see the structure (parts) of the ***cell membrane***…what would it look like?
In the space provided draw what the cell membrane looks like, be sure to label your drawing and again feel free to color your illustration.

8) The cell membrane is often described as a ***selectively permeable barrier***. In your own words, **explain** what this means. More specifically, how does the cell membrane determine what gets in or out of the cell?
Be as specific as possible in your explanation. You may use drawings to enhance your explanation.

Name:________________________________ ID:____________

Date:_________________________ Period:________________________

Treatment:_____________________

Cell Exploration-Posttest

1) In the space provided, *tell me everything that you know* about **cells**.

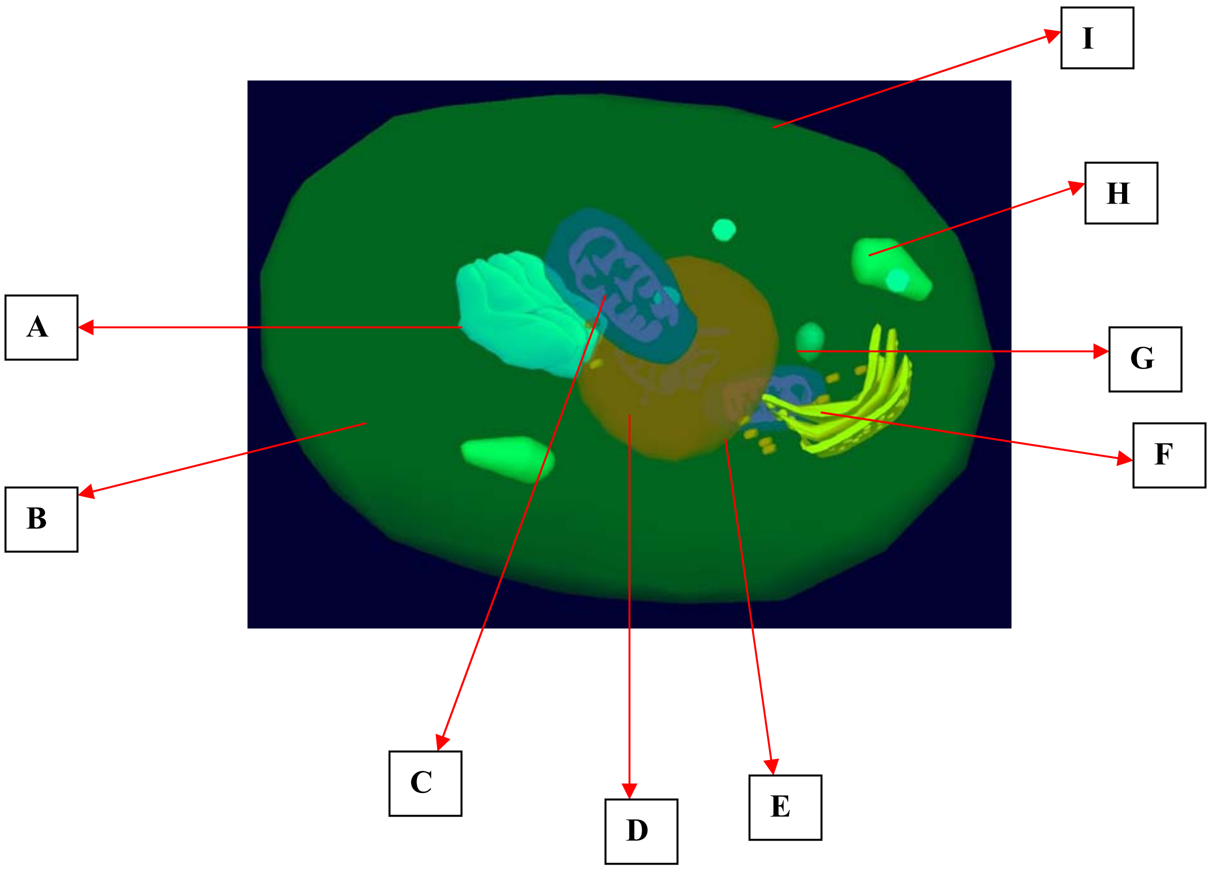
2) In the box, please draw and label a **cell**. Feel free to color your drawing.

3) A large 5 gallon glass container setting on a table is full of clear water. Several drops of dark blue dye are dropped on the surface of the water. In a paragraph, **explain** what will happen to the blue dye. **Be sure to write down any specific details about the process. Name the process.**

Name:____ ID:______________
Date:______________________________ Period:_____________________________
Treatment:_________________________

Cell Exploration-Posttest

4) Below is an illustration of a typical animal cell. Match the labeled cell parts with the correct name for that part. Place the letter on the line next to the name.



Cell Parts:

____ lysosome ____ cell membrane

____ mitochondrion ____ endoplasmic reticulum (ER)

____ cytoplasm ____ nucleus

____ vacuole ____ Golgi body

____ ribosomes

5) Another student states: “The passage of substances through the cell membrane is actually like the passage of substances through coffee filter paper.” Do you think that this statement sounds correct? **Please explain why or why not.**

Name:________________________________ ID:____________
Date:_________________________ Period:________________________
Treatment:_____________________

Cell Exploration-Posttest

6) Match the description of the cell part on the left with the correct name for that part & **put the letter on the line**.

Description	**Name of Part**
____ 1) controls the movement of materials into & out of the cell	**A)** vacuole
____ 2) directs all cell activity & contains genetic material that stores the information needed for the cell function	**B)** nucleus
____ 3) the site of cellular respiration that provides energy for the cell	**C)** endoplasmic reticulum
____ 4) a series of double membranes that helps move substances throughout the cell	**D)** ribosomes
____ 5) manufacture or make proteins for the cell	**E)** lysosome
____ 6) small sacs that contain powerful digestive enzymes; they help protect the cell by ridding it of “foreign invaders”	**F)** Golgi body
____ 7) packages proteins for the cell	**G)** mitochondrion
____ 8) act like storage tanks for the cell and may contain or store food, waste or water	**H)** cell membrane
____ 9) everything between the cell membrane and the nucleus; it consists of primarily of water but it also contains various organelles as well as salts, dissolved gasses and nutrients	**I)** cytoplasm

7) Suppose you could look deep inside a cell and see the structure (parts) of the cell membrane…what would it look like?
In the space provided draw what the cell membrane looks like, be sure to label your drawing and again feel free to color your illustration.

8) The cell membrane is often described as a ***selectively permeable barrier***. In your own words, **explain** what this means. More specifically, how does the cell membrane determine what gets in or out of the cell?
Be as specific as possible in your explanation. You may use drawings to enhance your explanation.

APPENDIX C

AFFECTIVE ASSESSMENT INSTRUMENT

Name:________________________________ ID:____________
Date:_________________________ Period:________________________
Treatment:_____________________

Assessment of Instructional Module

1) <u>Directions</u>: Listed below are a series of statements about the ***Cell Exploration*** program. Please indicate how you feel about each statement by circling the appropriate number according to the below scale:

1=Strongly Disagree
2=Disagree
3=Somewhat Disagree
4= Somewhat Agree
5=Agree
6=Strongly Agree

I was able to recall and use information presented in the program following its use.	**1 2 3 4 5 6**
I am more interested in this topic after using the program.	**1 2 3 4 5 6**
I feel that the reading level of the program was appropriate.	**1 2 3 4 5 6**
I was able to navigate through the program without difficulty.	**1 2 3 4 5 6**
The screen directions are consistent and easy to follow.	**1 2 3 4 5 6**
I felt that I was able to control pace and sequence of the program.	**1 2 3 4 5 6**
I believe that the graphics and animation enhanced the material presented in the program.	**1 2 3 4 5 6**
I found using the PHANToM joystick to explore the cell frustrating.	**1 2 3 4 5 6**
I found using the PHANToM joystick to explore the cell interesting.	**1 2 3 4 5 6**
I found using the PHANToM joystick to explore the cell boring.	**1 2 3 4 5 6**
When exploring the cell, I often lost my spatial orientation (i.e. I wasn't certain where the pointer was on the screen).	**1 2 3 4 5 6**
I believe that I have learned a lot about cells by participating in this activity.	**1 2 3 4 5 6**
I feel that the graphics and animation did NOT make the program any more interesting.	**1 2 3 4 5 6**
This program was different from the types of things we typically do in science class.	**1 2 3 4 5 6**

1=Strongly Disagree
2=Disagree
3=Somewhat Disagree
4= Somewhat Agree
5=Agree
6=Strongly Agree

I do NOT feel any more interested in this topic after using the program.	**1 2 3 4 5 6**
I was NOT able to remember and use information presented in the program following its use.	**1 2 3 4 5 6**
I found the program confusing and difficult to navigate through.	**1 2 3 4 5 6**
My favorite section of the program was exploring the parts of the animal cell.	**1 2 3 4 5 6**
My favorite part of the program was trying to pass the substances thorough the cell membrane.	**1 2 3 4 5 6**
My favorite part of the program was the animation about passive transport.	**1 2 3 4 5 6**

2) On a scale of 1-10, with a **1** being *not at all interesting* and a **10** being *extremely interesting*, how would you rate this program? **Circle the number of your choice below.**

1	2	3	4	5	6	7	8	9	10
not at all interesting									extremely interesting

APPENDIX D

DIFFERENTIAL IMPACT ASSESSMENT INSTRUMENTS

DO NOT WRITE IN THIS AREA Student Information/Computer Use

ID#:________________ Treatment:______________

Student Information Sheet

Name:________________________________ ____________________________
(Last) (First)

Gender: Male Female **(Circle one)**

Grade level: ______________________________

Age: __________________________

Ethnic Background: African American American Indian Asian

Hispanic Caucasian (White) Other **(Circle one)**

Do you play any organized (on a school or community team) sports? If so which:

____

Do you play any musical instruments? If so which: ______________________________

____

Do you have a computer at home? Yes No **(Circle one)**

Estimate the number of hours you spend in an average week ***using a computer outside of school***:

I do not use a computer outside of school

Less than 1 hour

1 to 3 hours **(Circle one)**

4 to 6 hours

More than 6 hours

Below is a list of activities that you may typically use a computer to do ***outside of school***.

Send/receive e-mail **Have "Real Time" conversations (chatting)**

Browse the World Wide Web **Work on school work**

Play video games

Rank the above activities **according to how often you do them** with #1 being what you do most often and #5 being the one you do least often. **Note:** You may have more than one activity on a line.

1) ____ (at least once a day)

2) ____ (2-3 times a week)

3) ____ (about once a week)

4) ____ (once a month)

5) ____ (hardly ever)

If you do play video games, which type (i.e. sports, combat, strategy, etc.) of games do you enjoy the most? Please be as specific as possible & name three (3) that you play often.

____

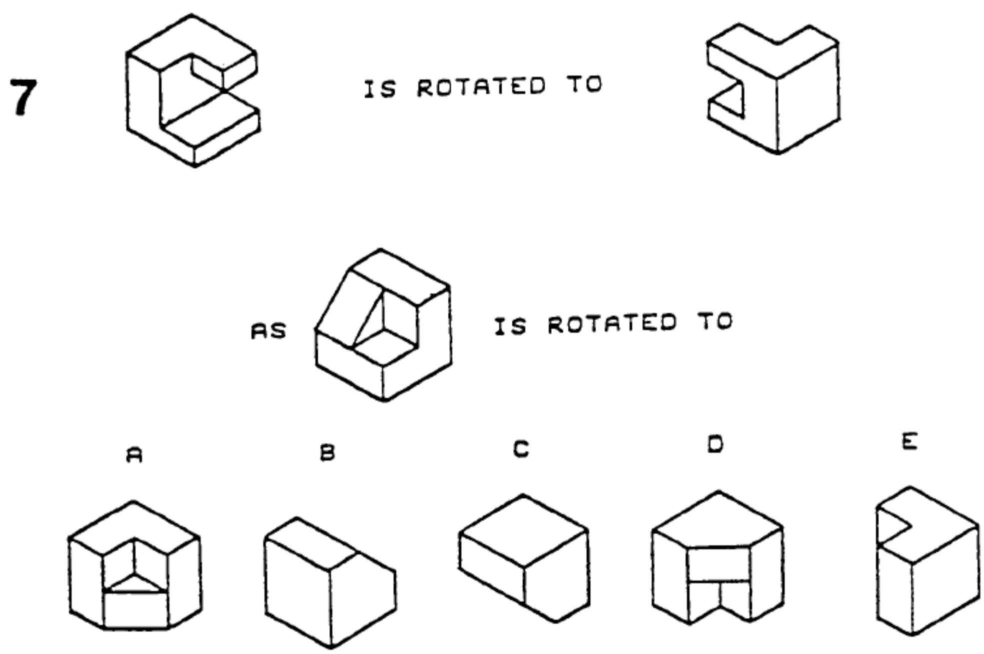
____

____

____

____

SAMPLE ITEM (#7) FROM THE 20-ITEM VERSION OF THE PURDUE VISUALIZATION OF ROTATIONS (ROT) TEST.



APPENDIX E

ADDITIONAL DATA SOURCES

Name:____________________________________ ID:_____________
Date:____________________________ Period:___________________________

Post-experience Interview Protocol
<u>Visual only</u> Group.

Researcher: *Do you think that being able to interact with (zoom in/out and rotate) the cell model in the 1st part of the program helped you learn about it? Why or why not?*

Researcher: ***Imagine*** *that you were able to actually feel the parts of the cell that you saw in the program. Do you believe that being able to "feel" the organelles (parts) of the animal cell would help you learn about them? Why or Why not?*

If student answers yes to the above question proceed:

Researcher: *What features, qualities, or characteristics of the cell and its organelles would you most want to be able to "feel"? Why?*

Researcher: *Do you believe that being able to "feel" the cell membrane would have helped you learn about its* ***structure*** *(how it is built)? Why or why not?*

Researcher: *Do you believe that being able to "feel" the cell membrane helped (would have helped) you learn about its* ***function*** *(how it works)? Why or why not?*

Name:___________________________________ ID:_____________
Date:___________________________ Period:__________________________

Post-experience Interview Protocol
<u>Visual + Haptic</u> Group.

Researcher: *Do you feel that being able to interact with (zoom in/out and rotate) the cell model in the 1st part of the program helped you learn about it? Why or why not?*

Researcher: *Do you believe that being able to "feel" the organelles (parts) of the animal cell helped you learn about them? Why or Why not?*

If student answers yes to the above question proceed:

Researcher: *What features, qualities, or characteristics of the cell and its organelles do you think you were able to "feel" the best?*

Researcher: *Do you believe that being able to "feel" the cell membrane helped you learn about its **structure** (how it is built)? Why or Why not?*

Researcher: *Do you believe that being able to "feel" the cell membrane helped you learn about its **function** (how it works)? Why or Why not?*

Researcher*: What are some other topics or ideas in science that you would like to be able to "feel" using a tool like the PHANToM?*

Name:________________________________ ID:____________
Date:_________________________ Period:________________________
Treatment:_____________________

Haptic Assessment

<u>Directions:</u> Answer each of the questions below by circling your choice. Examine the items that correspond to each question. You may touch the objects.

1) Which of these objects most closely resembles the **<u>cell</u>** from the Cell Exploration program?

A	**B**	**C**	**D**
GREEN SPONGE BALL (SOFT)	GREEN BALOON	GREEN CIRCLE (2-D)	GREEN STYROFOAM BALL (HARD)

2) Which most closely resembles the **<u>cytoplasm</u>** from the Cell Exploration program?

A	**B**	**C**
GREEN DISH SOAP	GREEN JELLO	GREEN WATER

3) Which most closely resembles the **<u>mitochondria</u>** from the Cell Exploration program?

A	**B**	**C**
ORANGE PEANUT SHAPE (2-D)	ORANGE *CIRCUS* PEANUT CANDY (SOFT)	ORANGE FOAM PEANUT (HARD)

4) Which most closely resembles the **<u>nucleus</u>** from the Cell Exploration program?

A	**B**	**C**
RED GUMBALL (HARD)	RED FOAM BALL (SOFT)	RED CIRCLE (2-D)