MULTIMODAL VIRTUAL LEARNING ENVIRONMENTS: THE EFFECTS OF VISUO-HAPTIC SIMULATIONS ON CONCEPTUAL LEARNING

by

Mayari I. Serrano Anazco

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Alejandra J. Magana Ph.D., Chair

Department of Computer and Information Technology

Dr. Bedrich Benes Ph.D

Department of Computer Graphics Technology

Dr. Paul Parsons Ph.D

Department of Computer Graphics Technology

Dr. Sanjay Rebello Ph.D

Department of Physics and Astronomy

Approved by:

Dr. Kathryne A. Newton

Head of the Graduate Program

I dedicate this dissertation to my family.

To my parents, Lourdes and Marco, who had provided me with guidance, nourishment, and encouragement.

To my sisters, Yamara and Dayuma, you make me happy.

To Brownie, Toby, Kike, and Bandido who are always by my side.

To my husband Diego, whom I love dearly.

And to my angel, Lana, the light of my life.

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LIST OF ABBREVIATIONS

AR	Augmented Reality
CATLM	Cognitive-affective Theory of Learning
CTML	Cognitive Theory of Multimedia Learning
DCT	Dual-cognitive Theory
DoF	Degrees of Freedom
EM	Electricity and Magnetism
FCI	Force Concept Inventory
JND	Just Noticeable Difference
MVE	Multimodal Virtual Environments
ROCkETEd	Research on Computing in Engineering and Technology Education
STEM	Science, Technology, Engineering, and Math
TEI	Tangible and embodied interfaces
TPTA	Telepresence and Teleaction Systems
VR	Virtual Reality

GLOSSARY

Affordance – “Relationship between the properties of an object and the capabilities of the agent that determine just how the object could possibly be used ” (Norman, 2013, p.11).

Cognition – “Cognitive processes are those responsible for knowledge and awareness. They include the processing of experience, perception, and memory, as well as overtly verbal thinking” (Blackburn, 2016).

Embodied cognition – “Mental processes are mediated by body-based systems, including body shape, movement, and scale; motor systems, including the neural systems engaged in action planning; and the system involved in sensation and perception” (Alibali & Nathan, 2012, p.248).

Grounding – “Mapping between an abstraction and a more concrete, familiar referent, such as an object or event, that facilitates meaning making ” (Alibali & Nathan, 2012, p.250).

Haptic – “Designating or involving technology (for entertainment, communication, etc.) that provides a user interface based on stimulation of the senses of touch and movement (kinaesthesia) ” (Dictionary, 1989).

Force feedback – “sensation of force, exerted on the body as a response to a particular act ” (Reiner, 1999, p.34). Mental imagery – “The act or process of forming mental images without stimulation of sense organs, or the mental images formed by memory and imagination, including not only visual images but also images from the other senses, such as hearing, taste, smell, and touch. The German psychologist Wilhelm (Max) Wundt (1832 - 1920) believed that images are one of the three basic elements of consciousness, together with sensations and feelings” (Colman, 2015).

Offline cognition – “The cognitive activities that occur in the absence of relevant environmental input” (Alibali & Nathan, 2012, p.250).

Sense organ – “A tissue sensitive to energies generally applied from the environment but also sensitive to those applied within the body ” (McLinden & McCall, 2016, p.22).

Simulation – "The process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system" (Shannon, 1998, p.7).

Stimulus – "Something that acts as a goad or spur to a languid bodily organ; an agency or influence that stimulates, increases, or quickens organic activity " (Dictionary, 1989).

Visuo-haptic – "Combination of touch and visual stimuli"

ABSTRACT

Author: Serrano Anazco, Mayari I. Ph.D.
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Major Professor: Alejandra J. Magana Ph.D.

Presently, it is possible to use virtual learning environments for simulating abstract and/or complex scientific concepts. Multimodal Virtual Learning Environments use multiple sensory stimuli, including haptic feedback, in the representation of concepts. Past research on the utilization of haptics for learning has shown inconsistent results when gains in conceptual knowledge had been assessed. This research focused on two abstract phenomena *Electricity and Magnetism* and *Buoyancy*. These abstract concepts were experienced by students using either visual, visuo-haptic, or hands-on learning activities. Embodied Cognition Theory was used as a for the implementation of the learning environments. Both phenomena were assessed using qualitative and quantitative data analysis techniques. Results suggested that haptic, visual, and physical modalities affected positively the acquisition of conceptual knowledge of both concepts.

CHAPTER 1. INTRODUCTION

This chapter provides an overview of the research study. It offers background information related to the research problem and its significance. Additionally, it presents the research statement of purpose, research questions, assumptions, limitations, and delimitations which define the project boundaries. This chapter concludes with a summary of the research project.

1.1 Background

Numerous sensations can be experienced through touch as it relies on the skin as its sensory organ (Heller & Gentaz, 2013). The skin is also the largest organ in the human body (Heller & Gentaz, 2013), its structure allows humans to perceive external stimuli through the whole body (Dargahi, Sokhanvar, Najarian, & Arbatani, 2012). The variety of receptors in the skin confer an advantage to the haptic perceptual system. From physical contact, the skin is capable of determining temperature (McLinden & McCall, 2016), force, the position of an applied force, vibrations, softness, texture, and viscoelasticity of the external stimuli (Dargahi et al., 2012).

Sensory stimulation through touch is necessary for the normal development of an organism (Ardiel & Rankin, 2010). In the womb humans first develop the sense of touch (Paterson, 2007), and because of its relevance in human development, its role has also been accounted for in the learning process. For instance, touch has been integrated into several learning theories as a key factor for learning such as cognitive constructivism (Chan & Black, 2006; Minogue & Jones, 2006), dual-cognitive theory (DCT) (Jones, Minogue, Oppewal, Cook, & Broadwell, 2006), cognitive-affective theory of learning (CATLM) (Moreno & Mayer, 2007; Schönborn, Bivall, & Tibell, 2011), embodied cognition (Escobar-Castillejos, Noguez, Neri, Magana, & Benes, 2016; Han & Black, 2011;

Magana & Balachandran, 2017b; Schönborn et al., 2011), and experiential learning (Kolb, 2014), among others. These theories argue that the sense of touch is necessary for enabling embodied experiences with objects and with other people. Such interactions depend on touch stimulation (Paterson, 2007).

The development of haptic technology has enabled the introduction of touch stimuli via simulations. In educational contexts, simulations allow users to observe, experience, and/or interact with phenomena that could be difficult to perceive or cannot be experienced otherwise (DAngelo et al., 2014). Additionally, computer-based simulations allow students to modify variables in an error-free frame as many times as required; this is difficult to produce using physical props. Educational computer-based simulation affordances are restricted by the technology available in educational settings and the complexity of concepts addressed. Several concepts in science and engineering have an abstract nature. Finding new ways to conceptualize and describe abstract phenomena is fundamental for scientific progress (Boroditsky & Ramscar, 2002). Haptic technology can have the potential to make abstract concepts more concrete by supporting exploration through the sense of touch. Haptic technology has already been used to simulate material properties (Klatzky, Pawluk, & Peer, 2013), medical training (Escobar-Castillejos et al., 2016), and learning (Clark & Jorde, 2004; Magana & Balachandran, 2017b; Minogue & Jones, 2006).

Numerous concepts in physics are abstract in nature. Because of this, common teaching approaches focus on mathematical representations without providing embodied learning experiences (Han & Black, 2011). Early work has tried to integrate haptic devices into existing scientific visualization tools (Durbeck, Macias, Weinstein, Johnson, & Hollerbach, 1998; Sato, Liu, Murayama, Akahane, & Isshiki, 2008). Brooks, Ouh-Young, Batter, and Jerome (1990). This work suggested that haptic feedback can help users understand and perceive force fields. Haptic output has also been used to represent and understand volumetric data of simple and complex geometries (Qi, 2006). Magana et al. (2017) suggested that abstract concepts learning could benefit from the ability to touch or manipulate objects when compared with teaching material that uses only visual input. Research on the subject has predominantly looked at benefits of visual vs. haptic modality or vice-versa. However, how to appropriately integrate haptic feedback on the simulation of abstract concepts is still an open question. This study's goal was to explore how visual and visuo-haptic simulations can affect the conceptual learning of abstract concepts in physics such as electricity and magnetism, and buoyancy.

1.2 Significance

Many industries and branches of academia depend on professionals capable of understanding complex scientific concepts (Dede, Salzman, Loftin, & Sprague, 1999). In science, technology, engineering, and mathematics (STEM) fields complex concepts can increase their difficulty given their invisible, abstract, and multidimensional nature (Dede et al., 1999). To address cognitive obstacles when learning abstract concepts Magana et al. (2017) suggested using a combination of different modalities and teaching methods. Thus research on new approaches to facilitate abstract learning of complex concepts is needed.

Computer-based simulations have become a useful tool for students and teachers (Proserpio & Gioia, 2007). The ability to integrate haptic feedback to computer-based simulations has generated new learning environments that have the potential to recreate abstract phenomena into tangible feedback. Research about the impact of haptic technology on learning has mainly focused on contrasting haptic feedback with visual feedback. This work has resulted in inconsistent findings (Zacharia, 2015). The optimization of multimodal learning environments, environments that provide more than one modality/type of feedback, can lead to new ways of interactions and learning gains improvement.

1.3 Statement of Purpose

The purpose of this study is to investigate the effect of using different visuo-haptic configurations for learning abstract force related physics concepts. To this end, learning environments used in this study were configured to display full visual feedback (single modality), haptic feedback with minimal visual cues (single modality), visual and haptic feedback in unison (dual modality), and the haptic feedback with minimal visual cues followed by full visual feedback (sequenced modality). Modality configuration efficiency was ascertained by the conceptual knowledge accuracy level. Additionally, participants' alternative conceptions were also examined.

Embodied cognition theory was used as a baseline to create multimodal learning environments and assessments. The experiments conducted aimed to represent abstract phenomena with scientific accuracy and sensory feedback that mimicked or represented the system elements.

The results obtained in this study by contrasting dual, sequenced, and single modalities of visual and haptic feedback contributed towards obtaining educational simulation approaches that may greatly enhance conceptual learning of abstract phenomena. This study addressed two types of physics phenomena: non -linear (the relationship between force and motion) and linear (buoyancy).

1.4 Research Question and Hypothesis

The purpose of this study was to investigate the efficiency of using visuo-haptic simulations for learning abstract linear force-related (i.e., buoyancy) and non-linear force-related (i.e., electricity and magnetism) physics concepts. To this end the following specific questions guided this research:

- Does the addition of tactile stimulus to an electricity and magnetism computer-based simulations result in higher conceptual knowledge about the subject than using computer-based simulations alone?

  H_{o1}: The use of tactile stimulus has no effect on final conceptual knowledge about Electricity and Magnetism.

  H_{a1}: The use of tactile stimulus results in higher conceptual knowledge about Electricity and Magnetism.

- Does the modality (single, dual, sequenced) in which tactile and visual feedback is delivered affect students' development of conceptual learning of electricity and magnetism concepts?

  H_{o2}: The type of learning modality used for interaction by students has no effect on their final conceptual knowledge about Electricity and Magnetism.

  H_{a2}: The type of learning modality used for interaction by students will affect their final conceptual knowledge about Electricity and Magnetism.

- Does a visuohaptic simulation influence development of conceptual learning of buoyancy when compared to a laboratory hands-on experience?

  H_{o3}: A visuo-haptic simulation has no effect on their final conceptual knowledge about buoyancy.

  H_{a3}: A visuo-haptic simulation will affect their final conceptual knowledge about Buoyancy.

Additionally, this research study addressed two research questions qualitatively:

- How does the interaction with a visuo-haptic simulation influence scientific conceptualization of electricity and magnetism?

- How does the interaction with a visuo-haptic simulation influence scientific conceptualization of buoyancy?

1.5 Assumptions

The assumptions for this study include:

- Participants provided true and thoughtful responses to assessments.

- Participants did not help each other to respond to the assessment questions.

- Equipment used in the experiments would perform without error and within expected specifications.

- The time allowed for interaction with the learning environments was enough to complete all the activities and assessments.
- The research methodology implemented was appropriate to answer the study's research questions.

1.6 Limitations

The limitations of this study include:

- This study was limited to students enrolled in PHYS 215 *Physics for Elementary Education*, at the West Lafayette campus of Purdue University.
- The study was dependent on the participants' willingness to fill out the assessments.
- The time frame to run the experiments was 1.5 hours.
- The research assessed the activities immediately after exposure and for some experiments two weeks later.

1.7 Delimitations

The delimitations for this study include:

- The time frame of five semesters (Spring 2016, Fall 2016, Spring 2017, Fall2017, and Spring 2018) to collect data.
- The experiments used one visuo-haptic simulation for electricity and magnetism, one visuo-haptic simulation for buoyancy, and one laboratory hands-on activity for buoyancy.
- The study was conducted at Purdue University in the West Lafayette facilities.

1.8 Document Organization

This dissertation contains seven chapters and three appendices. Chapter 2 provides an outline of relevant literature on difficult concepts in science, electricity and magnetism, buoyancy, human perception, and haptics. Chapter 3 provides details about Grounded Cognition and specifically Embodied Cognition Theory which was used as a theoretical framework. Chapters 4 and 5 provide a detailed overview of the learning design, research design, and results for the studies. The remaining chapters present discussion, implications, limitations, and future work.

1.9 Summary

This chapter provided an overview of the research project including significance, research questions, assumptions, limitations, delimitations, definitions, and other background information. Additionally, an outline of the document structure was provided.

CHAPTER 2. LITERATURE REVIEW

2.1 Difficult Concepts in Science

The ability to understand complex information is an important skill for future scientists and engineers. Several branches of industry and academia depend on science and engineering professionals capable of understanding and utilizing complex concepts. However, learning and teaching complex concepts is not an easy quest (Dede et al., 1999). Moreover, comprehending abstract scientific content requires flexible mental models of phenomena that most of the time students had never experienced (Dede et al., 1999; Squire, Barnett, Grant, & Higginbotham, 2004). Bagno, Eylon, and Ganiel (2000) suggested that manifold difficulties, in the short term, arise when there is a lack of knowledge organization in the process of resolving complex problems. Mastering complex concepts could be especially challenging in science, technology, engineering, and mathematics (STEM) fields, given that such fields deal with abstract, non-visible, or multidimensional phenomena, which could increase their difficulty for learning (Dede et al., 1999; Magana & Balachandran, 2017b; Squire et al., 2004).

For understanding abstract phenomena, students are required to build accurate mental models by integrating complex abstractions and invisible components without ever experiencing them (Squire et al., 2004). Magana et al. (2017) suggested that invisible, counterintuitive, abstract, and non-tangible concepts can create conceptions that do not match the scientific concepts. In other words, students may think that they understand a concept, but their grasp is significantly different from the scientific explanation, resulting in alternative scientific conception also known as misconception (Kalman, 2017). Moreover, research suggests that students often do not abandon their alternative conceptions easily. Instead, they assimilate scientific concepts into their old conceptions (Kalman, 2017). To transform alternative conceptions in favor of scientific concepts, the learning process should elicit conceptual change (Dega, Kriek, & Mogese, 2013). To spark conceptual change, it is necessary to confront students with scientifically correct models that can be contrasted with the learner's naive theories (Vosniadou, 2007). To create accurate models students need to recognize inconsistencies between scientific and their naive theories. Additionally, students need to use deliberate and intentional learning mechanisms to avoid the creation of inaccurate models (Vosniadou, 2007).

To overcome cognitive obstacles when learning abstract concepts, it is recommended to use combinations of different modalities and teaching methods (Magana et al., 2017). The use of computer simulations, tangible representations, and non-textual representations to portray complex scientific concepts may encourage science learning (Squire et al., 2004). Computing opens a new way of modeling complex phenomena. Technology such as virtual reality (VR) can allow immersion in engaging learning activities and offers multisensory cues (Dede et al., 1999). The inclusion of additional touch sensory information can contribute to the creation of embodied memories which can help recall the learning experience (Magana & Balachandran, 2017b). Tangible manipulatives, physical or virtual, generate motor schemes that can be map to metaphors to ground science concepts by creating a perceptual knowledge anchor (Zacharia, 2015).

2.1.1 Teaching Methods in Physics Educational

The traditional teaching of physics concepts often does not result in robust conceptual understanding (Finkelstein, 2005). Many physics concepts are difficult to understand and non-engaging (Jose, Akshay, & Bhavani, 2014). For example, it is difficult to understand electromagnetic induction, energy, electricity and magnetism, and electric potential concepts, as those generally possess alternative conceptions (Magana et al., 2017; Planinic, 2006). Furthermore, physics concepts are deeply interrelated, but those are usually studied as separate units (Planinic, 2006). Comprehension and recall of central concepts are hindered by traditional teaching methods within separate domains (Bagno et al., 2000). This knowledge fragmentation obstructs the learner's ability to link domain-specific examples of the same concept (Bagno et al., 2000).

Difficulty in understanding physics concepts can be carried out up to tertiary education. For instance, Redish (2000) determined that undergraduate students with an understanding of basic physics concepts should score above 80% in The Force Concept Inventory (FCI). However, when applied to typical undergraduate students enrolled in an introductory first-semester physics class, on average, the score has been between 40% and 50% at entry; and between 50% to 60% by the end. Moreover, advanced physic students with ample knowledge of physics content still have struggled to correct their mistakes with no explicit mediation of the instructor (Mason & Singh, 2010).

To address the challenges of traditional methods, Squire et al. (2004) suggested the use of demonstrations, labs, experiments, and visualizations to supplement mathematical formulae for teaching physics. Specifically, the use of computer simulations allows students to experience abstract, complex concepts in environments that conform to physics' rules (Squire et al., 2004). Conceptual learning is benefited by the use of simulations that enable visualization of invisible and complex concepts and exploration of conflicting events (Dega et al., 2013).

2.1.1.1 Electricity and Magnetism

Electricity and magnetism incorporate the concepts of charge, field, electric force, potential, potential difference, Gauss's law, magnetic field, electric current, electromagnetism, electrostatics, Faraday's law, and flux to name a few (Chabay & Sherwood, 2006). These are complex concepts in physics as they incorporate abstract relationships that are challenging to learn (Dega et al., 2013). In electricity and magnetism numerous concepts are microscopic (i.e. electrons) or abstract (i.e. field) (Chabay & Sherwood, 2006). Furthermore, abstract concepts, such as electromagnetism, are challenging even for the advanced physics' students (Squire et al., 2004).

Mathematical and graphical representations are generally utilized for depicting fields in physics (Reiner, 1999). Conceptualization of electric fields and their behavior need to integrate three-dimensional and abstract representations, but scarcely analogies from the students' everyday experiences can be tied with this phenomenon (Squire et al., 2004). Furió and Guisasola (1998) suggested that undergraduate students present ontological and epistemological difficulties applying the concept of electric field to solve problems.

In electromagnetism the understanding of how a test charge is propelled in a field is a commonly confusing concept concerning electric fields. To understand this concept the learner needs to discern the distribution of forces in the system and how they translate in to test charge motion (Squire et al., 2004). Magana and Balachandran (2017a) reported that students accurately represented the behavior of forces around different charges when haptic feedback was coupled with minimal or rich visual cues.

Guisasola, Almudi, and Zubimendi (2004) studied alternative conceptions related to the concept of a magnetic field. The findings showed that the majority of the participants, undergraduate students of engineering and physical science, couldn't identify the souse of the magnetic field. Guisasola et al. (2004) also reported that the concepts of magnetic force and magnetic field were constantly mixed up.

Dega et al. (2013) suggested that in undergraduate education, sequentially structuring instruction is inadequate in lowering alternative conceptions on electricity and magnetism concepts. On the other hand, the use of simulations to represent electromagnetism concepts such as vector field visualization can enable students with the ability to look at changes in the field lines leading to an innate understanding of the system's properties. This level of abstraction cannot be achieved with only mathematical representations of this phenomenon (Squire et al., 2004). Dega et al. (2013), suggested less guided interactive simulation explorations could be benefited by cognitive perturbation approach rather than cognitive conflict using interactive simulations for eliciting conceptual changes in electricity and magnetism mental models in undergraduate first-year physics students. The cognitive perturbation approach allows the use of alternative conceptions as the base for the construction of a scientific representation of the concept, this is not permitted by the cognitive conflict approach.

2.1.1.2 Buoyancy

Constructing a scientifically sound explanation of buoyancy can be difficult (Yin, Tomita, & Shavelson, 2008). Biddulph and Osborne (1984), suggested that children can possess different definitions of floating. For instance, children ages seven to ten years were not aware that a single explanation can be applied for floating/sinking of different objects. Children and adults can encounter the same difficulties when making density-based predictions about floating or sinking, specifically, an object's weight and volume can interfere constantly in providing accurate predictions (Kohn, 1993). Even students from introductory physics courses may need instruction to distinguish between mass and volume concepts (Heron, Loverude, Shaffer, & McDermott, 2003). Furthermore, undergraduate students that completed instruction in hydrostatics struggled in identifying the forces interacting in a sinking/floating system (Loverude, Kautz, & Heron, 2003).

The phenomenon of floating and sinking has been extensively addressed since initial grades of formal education (Kallery, 2015). Traditionally, highly dynamic simulations with visual feedback have been successfully applied to help focus attention and to improve understanding of key features of physics, chemistry, economics, and biology concepts (De Jong et al., 1999). The benefit of using simulations seems to reside on their affordances and versatility to help students understand conceptual relationships by constructing visual connections between multiple representations (Lindgren & Schwartz, 2009).

2.2 Human Perception

Learning could be defined as the construction of knowledge, assuming that previous knowledge provides meaning to the sensory information perceived by a learner (Minogue & Jones, 2006). An organism comes to know the world by its representation (Shapiro, 2010). Humans navigate, explore, and learn about their environment by using their senses: sight, hearing, touch, smell, and taste (Dargahi et al., 2012). Our senses specialize in different stimuli perception: (i) Vision is excellent for perception of spatial information, (ii) Audition is the most effective type of perception for temporal stimuli, since it is specialized on perception of sequential information; however, the sequence of the stimuli cannot be changed since it carries a specific meaning, (iii) Touch is also sequential; exploration is not linear or in a specific order, which makes it modality spatial (Hatwell, Streri, & Gentaz, 2003; Sigrist, Rauter, Riener, & Wolf, 2013).

An interesting question arises when we think about the amount of stimuli we can perceive. Why this amount? The answer lies in two terms: degeneracy and reentry. Degeneracy is a neural construction that uses more than one neuro signal to carry out a single function, creating redundancy in the system and allowing the functions to be carried out even when one of the neurosignals is missing (Smith & Gasser, 2005). In other words, still in the absence of one sense, we can still successfully determine what we need by the utilization of the other senses. An example of this occurs in the absence of visual perception, touch becomes an effective device to interact with our surroundings or for object recognition (Minogue & Jones, 2006). Reentry introduces the notion of sensory systems educating one another, creating simultaneous representation across sensory systems. For example, when a person is introduced to a new fruit, all the sensory systems register and save the relevant characteristics. If later the person is presented with an image of the fruit, they will be able to retrieve the smell, flavor, and texture associated with that particular object Smith and Gasser (2005). Cognitive modularity could be used as a basis to understand how our senses cooperate and share information. Modularity suggests that each sense accepts information from specific inputs and processes this information; then the new abstracted information is delivered into an information repository that is shared by all the senses (Gaspar, Fontul, Henriques, & Silva, 2017).

2.2.1 Touch

Tactile sensitivity is the first sense to be developed. This development happens in the first weeks of fetal life. This sense differs from the other senses in the fact that its receptors are spread over the whole body (Dargahi et al., 2012; Hatwell et al., 2003; Paterson, 2007). This characteristic makes the tactile perceptual field limited by the area of contact (Hatwell et al., 2003; Hatzfeld & Kern, 2014b). Different types of sensory information is collected depending on the receptor and type of touch used (active, passive) (McLinden & McCall, 2016). Active touch involves the exploration of an object with the intention of obtaining information (McLinden & McCall, 2016). Passive touch, also known as cutaneous or passive tactile perception, involves contact of the skin with an object without active manipulation (McLinden & McCall, 2016). Passive touch uses receptors located in the skin to perceive external cues. Throughout the skin, humans are capable of detecting softness, texture, force and point area of application, vibration, and viscoelasticity (Gaspar et al., 2017). The interpretation of the tactile sensory data enables us to determine objects' shape, temperature, fine features, and mass distribution (Dargahi et al., 2012).

2.2.2 Importance of touch in the learning process

In educational contexts, two types of learning could be distinguishable: (i) information acquisition in which the objective is to add information to the memory of the learner (i.e. textbook lesson), and (ii) knowledge construction that encompasses the creation of mental representations by actively making sense of the instructional materials (Moreno & Mayer, 2007). Traditional classroom instruction leans towards information acquisition or memorization over knowledge construction and understanding of concepts (Chan & Black, 2006). The educational system has for centuries favored verbal and visual instruction (Moreno & Mayer, 2007). However, touch can also be used to recall representations in our memory (Alexander, Johnson, & Schreiber, 2002).

Currently, in primary, secondary, and even tertiary learning curricula, touch is not often used as a channel for conceptual learning, even though it is the main way of interaction with the world (Shaikh et al., 2017). However, there is a tendency to incorporate more hands-on inquiry teaching on the educational curriculum (Williams, Chen, & Seaton, 2003). Hands-on learning activities actively involve students in object manipulation, which can help to develop perceptual, muscular, and psychomotor skills. Haptic experiences are fundamentally "hands-on experiences and can prompt students to explore and manipulate the learning materials (Jones, Minogue, Tretter, Negishi, & Taylor, 2006). Creation of manipulatives that can detectibly symbolize intangible concepts or ideas could provide concrete experiences for students interacting with them (Minogue & Jones, 2006). Manipulatives could also help learners to embed the cognitive activity in the real or virtual setting, therefore, reducing the cognitive load and adopting sensorimotor sequences (Magana & Balachandran, 2017b).

2.3 Haptics

The term haptic touch is utilized to represent the use of active touch in the process of seeking information (McLinden & McCall, 2016). The root of the word haptics comes from the Greek words "*haptios*" which means "something which can be touched" (Hatzfeld & Kern, 2014b), "*haptikos*" means "able to touch" (McLinden & McCall, 2016), and "*hapteshai*" which refers to "able to hold" (Minogue & Jones, 2006).

Nowadays, haptic research incorporates the study of the sense of touch and the interplay between human and environment through taction including extraction of information and manipulation of the environment (Han & Black, 2011; Minogue & Jones, 2006). The field of haptics incorporates virtual and real objects and/or environments, and humans or machines could perform the touch input and output of information (El Saddik, 2007). Haptic technology enables users to feel simulated object's physical properties (hardness, weight, inertia) and/or explore virtual environments (Magana et al., 2017).

Haptic systems allow interaction with virtual and real worlds using cognitive, sensory, motor, mechanical capabilities (Hatzfeld & Kern, 2014b). Haptic interactions are classified as perceptual and motion control (Hatzfeld & Kern, 2014b). Hatzfeld and Kern (2014b) classified haptic perception in tactile and kinesthetic. Tactile perception depends on the sensory receptors in the skin and it is responsible for the recognition of mechanical, thermal, electrical, chemical stimulation (Hatzfeld & Kern, 2014b). Kinesthetic sensory data integration allows humans to establish body orientation, limb alignment, joint position, and muscle tension (Hatzfeld & Kern, 2014b). Kinesthetic perception utilizes neuromuscular spindles and Golgi tendon organs to detect strain in the skeletal muscles and perceive mechanical tension respectively(Hatzfeld & Kern, 2014b). Figure 2.1 presents the receptors and perception types for tactile and kinesthetic haptic perception.

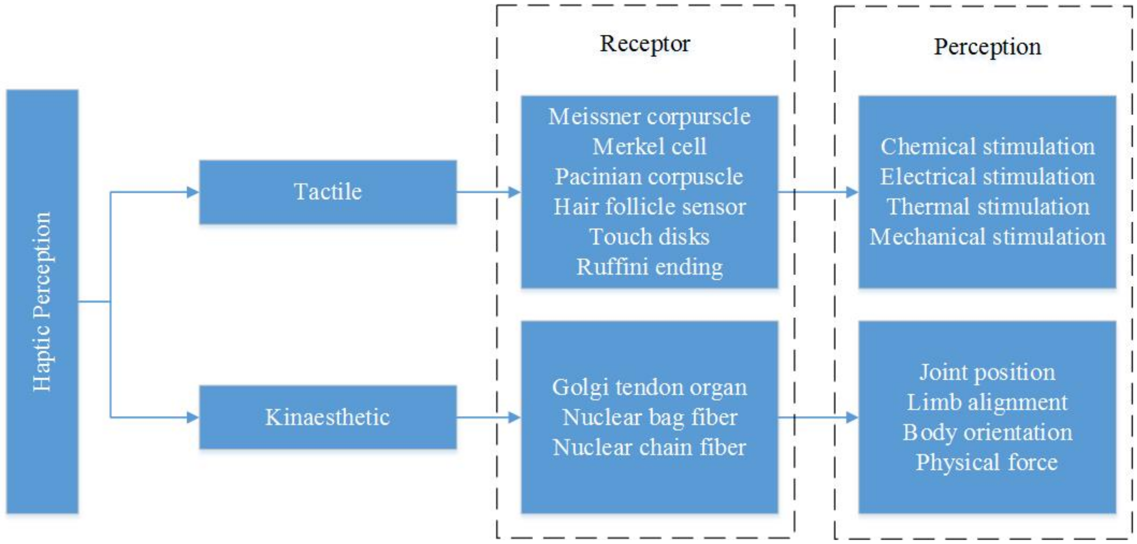


Figure 2.1. Haptic perception and receptors (Hatzfeld & Kern, 2014b).

A haptic system is a perceptual system used to recognize and differentiate objects through manipulation (McLinden & McCall, 2016). When dealing with object recognition, the data collected by cutaneous perception is processed by motor subsystems that can interpret hand movement patterns (kinesthetic perception) to extract stimuli characteristics (Gaspar et al., 2017). This interaction creates a system known as haptic, tactilo-kinesthetic, or active touch (Hatwell et al., 2003). That is to say, active touch involves the intentional action of the individual (Jones, Minogue, Tretter, et al., 2006).

El Saddik (2007) classified haptic research as follows:

- Human haptics: study cutaneous and kinesthetic sensations and its significance in human sensing and manipulation.
- Machine haptics: this area of haptics refers to the design and fabrication of haptic devices.
- Computer haptics: concerning the development of algorithms to render haptic information in virtual environments.
- Multimedia haptics: study of the potential multimedia applications of haptics.

2.3.1 Haptic Interfaces

In the user-computer interface, haptic technology can be used as an input/output channel (Hamza-Lup & Stanescu, 2010). Haptic interfaces are used to facilitate interactions in virtual and real environments and feel the virtual components of the simulation thus creating a more realistic experience for the user (Hatzfeld & Kern, 2014b; Jacobson, Kitchin, & Golledge, 2002; Magana & Balachandran, 2017b; Williams et al., 2003).

Implementation of haptic interfaces requires the use of artifacts that allow simultaneous information exchange between the user and the computer known as haptic devices (Minogue & Jones, 2006). These artifacts can generate haptic feedback by pneumatic, vibrotactile, electrotactile, and electromechanical stimulation (Jones, Minogue, Tretter, et al., 2006). Haptic devices can be active or passive. Active devices supply computer-controlled feedback to the users, while passive devices receive input applied by the user (Robles-De-La-Torre, 2008).

Haptic systems rely on the hands as perceptual systems and motor organs that execute actions (Hatwell et al., 2003). The human hand, including the wrist, has 27 degrees of freedom (DoF). DoF refers to the number of independent movements carried out by the mechanism (El Saddik, 2007). Commercially available devices allow movement with several degrees of freedom (DoF). Devices with more DoFs, are more difficult to produce but have greater precision (Stanney & Hale, 2014). For example, a device that can only exert vibrations is a unidirectional mechanism and has 0 DoF. Haptic devices with 3 DoF allow movement in three-dimensional (3D) environments (Escobar-Castillejos et al., 2016). Figure 2.2 shows some haptic devices commercially available.

Along with DoF, haptic devices are also characterized by the refresh rate, which represents the higher speed of force or toque generation (El Saddik, 2007). Hatzfeld and Kern (2014b) identified the following as the main applications of haptic systems:

- Telepresence and teleaction systems (TPTA) to interact mechanically with remote environments.
- Enhancement of virtual environments.

Figure 2.2. Commercial haptic interfaces: (a) Microsoft Sidewinder Joystick - 2DoF (Hale & Stanney, 2014), (b) Noviant Falcon - 3DoF (HapticsHouse.com, 2017), (c) Omega 6 - 6 DoF (Force Dimension, 2017), (d) Phantom Omni - 6 DoF (Delft University of Technology, 2017), and (e) Quanser HD2 - 7 DoF (Quanser, 2017).

- Communication, where the systems could be used to convey information in a discrete way (i.e. vibration).

Multidirectional communication makes haptic devices fitted for the implementation of a highly interactive multimodal learning environment (Moreno & Mayer, 2007). Additionally, haptic technology can offer a personalized and interactive user experience (Ciampa, 2014).

2.3.2 Haptic technology for learning

The widespread usage of computers and the Internet for learning tasks has promoted the creation of computer-based simulations and virtual learning environments for large-scale utilization (Escobar-Castillejos et al., 2016). The application of well-designed computer simulations as pedagogical instruments has been extensively studied and proven to greatly aid learning, spark curiosity, and sustain the interest of students when compared with instruction deprived of computer simulations (Magana & Balachandran, 2017b). Humans use inputs from multiple senses to interpret and navigate their surroundings (Williams et al., 2003). However, simulations enhanced by visualization are predominantly preferred discerning a behavior, process, or concept (Clark & Jorde, 2004).

Haptic interfaces offer something unique to virtual learning environments: bidirectionality, which opens the door to user active participation in the system (refer to Figure 2.3) (El Saddik, 2007; Minogue & Jones, 2006). Sigrist et al. (2013) stated that bidirectionality can enable complex motor learning, which is defined as a "lasting change in the motor performance caused by training" (Sigrist et al., 2013, p.22). Most medical applications of haptics prompt this kind of learning, especially for surgical training (Dalgarno & Lee, 2010).

Interactive technologies, such as haptic equipment, can improve the learning environment's ability to provide feedback, make the content easy to understand and potentiate students' learning by doing (Council et al., 2000). The availability of a haptic channel in the learning process offers instant sensorimotor feedback about the interaction and the functional relationships present in the learning setting (Chan & Black, 2006). Furthermore, haptic technology could facilitate students to full immersion within the learning process by exploiting experiential, kinesthetic, tactile, and embodied knowledge (Minogue & Jones, 2006).

By involving more channels of communication individuals acquire more information from the learning process (Chittaro & Ranon, 2007). Multimodal Virtual Environments (MVE), by definition, convey information by using multiple modalities. The implementation of MVEs can help learners to connect theory and reality (Hamza-Lup &

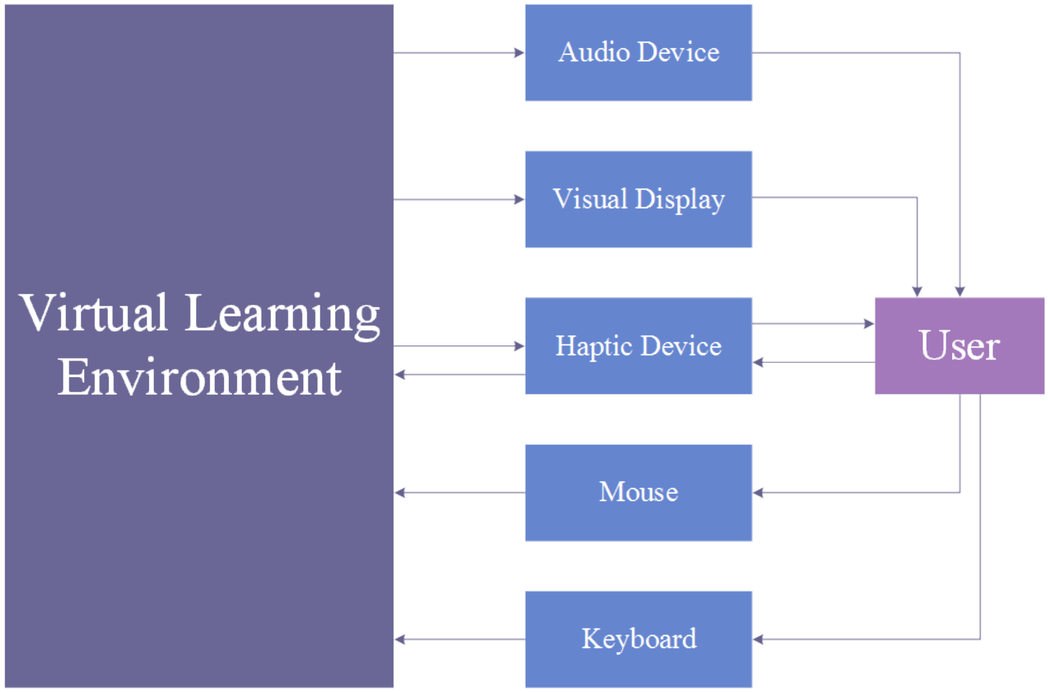


Figure 2.3. Illustration of the information pathway in virtual learning environments that incorporate visual, audio, and haptic feedback.

Stanescu, 2010). It is suggested that neural activation is reached earlier by multimodal stimuli than by unimodal stimulus, thus multimodal stimuli detection is faster and more precise than unimodal. Moreover, multimodal learning enhances not only multimodal representations but also unimodal connections. These results indicate that unimodal learning is inferior to multimodal environments and that motor learning is enhanced by multimodal feedback (Sigrist et al., 2013).

Sigrist et al. (2013) also suggested that multimodal learning reduces the cognitive load by distributing the processing of information. MVEs commonly use visual and audio modalities to produce descriptive explanations of numerous concepts (Hamza-Lup & Stanescu, 2010). This tendency may be given because the technology available was not able to render appropriate feedback for other senses (Jacobson et al., 2002). Currently, existing technology has made haptic devices commercially available thus allowing its incorporation in education, gaming, and industrial applications.

Virtual learning environments that provide more than one stimulus (i.e. audio, visual, or haptic) can deliver information more efficiently to the learner because the channel of communication is enriched with more information (Hamza-Lup & Stanescu, 2010). Also, adding touch cues to the learning environments could potentially enhance the learning quality and improve the learning attributes by permitting exploration (Escobar-Castillejos et al., 2016; Magana & Balachandran, 2017b). It is central to mention the importance of proper design in interactive learning environments because interactivity does not automatically create understanding and can even lead to an unnecessary load that can disrupt deep learning (Moreno & Mayer, 2007). Simulations in 3D with only haptic feedback may provide an unusual feeling, while only visual stimuli could lead to ambiguity (Paterson, 2007). Haptic information coupled with visual cues may enhance the significance of the available visual components. Also, the addition of a haptic component to the virtual experience may increment the simulation's realism and may entail a boost in the user's immersion in the simulated environment (Jacobson et al., 2002).

In the medical field, the use of haptic technology coupled with high fidelity visualizations and auditory cues have facilitated the training and teaching of concepts related to invasive surgery, wound closure, laparotomy, or other activities when instructors are scarce (Issenberg, Gordon, Gordon, Safford, & Hart, 2001). These applications frequently focus on the mechanization of a movement and the users are assessed in the accuracy of its interaction with the device itself and not content knowledge or translation to other types of procedures. Medical applications also include the testing of virtual reality systems. C. J. Luciano et al. (2011) developed a system denominated "Immersive Touch" which allowed users to receive "real-time haptic feedback with a high-resolution stereoscopic display" (C. J. Luciano et al., 2011, p.14) of thoracic pedicle screw positioning. The system also provided multiple views of the trajectory of the drill. The results showed performance similar to the one found in the literature for this practice. For dental training, Yoshida et al. (2011) constructed a virtual multi-layered tooth model that offered different mechanical hardness by utilizing haptic technology. The researchers concluded that this system closely resembled the feeling of a real tooth (Yoshida et al., 2011).

Vision and touch are highly redundant when acquiring environmental spatial knowledge and properties of objects (Hatwell et al., 2003). In human minds, there is a relationship between the objects' appearance and its tactile sensation (Amedi, Malach, Hendler, Peled, & Zohary, 2001). The information received by touch and vision can be shared for processing when extracting objects' basic features, thus cooperating in the object identification process (Amedi et al., 2001; Kitada, 2016).

Virtual reality environments enhanced with visual and haptic feedback can create knowledge-building experiences in a novel learning setting (Schönborn et al., 2011). Furthermore, visuo-haptic simulations could enhance the learning of simulated concepts and the enhance retention of the transmitted information (Magana & Balachandran, 2017b).

Haptic technology can be utilized as a novel way to enhance virtual educational environments by including tactile cues in learning activities (Dalgarno & Lee, 2010; Escobar-Castillejos et al., 2016). This approach may offer students to feel phenomena in ways in which books, illustrations, and animations cannot (Bivall, Ainsworth, & Tibell, 2011). Minogue and Jones (2006), inferred that manipulation of physical or virtual objects may lead to a deeper understanding of them.

The use of haptic enhancement is advantageous for teaching and /or learning difficult basic scientific concepts in the field of physics (Jose et al., 2014). Haptic feedback could be potentially useful when dealing with abstract concepts and invisible or non-tangible phenomena, which are commonly difficult to understand and may hold misconceptions, that could be difficult to detect and correct (Magana & Balachandran, 2017b).

In this regard, it is reasonable to state that the utilization of haptics in education can promote physical, temporal, and spatial knowledge (El Saddik, 2007). One important limitation of haptic enhancement, given due to currently available technology, is that many learning activities depend on point-probe exploration (Jones, Minogue, Tretter, et al., 2006). This characteristic seems to be restricting the educational implementation of haptics.

Additionally, haptic components in an MVE offer an additional channel of information that could be employed by visually impaired users (Jacobson et al., 2002). Jones, Minogue, Tretter, et al. (2006) explored the efficacy of haptic feedback for enhancing learning about cell morphology in visually impaired middle school kids. The results suggest that participants significantly improved their capacity to recognize cell organelles. Additionally, participants found the activity engaging and interesting (Jones, Minogue, Tretter, et al., 2006). However, findings regarding the integration of haptic feedback have yield mixed results (Yuksel et al., 2019; Zacharia, 2015).

2.3.2.1 Learning theories pertinent to haptic technology

The sense of touch could conform to multiple learning theories statements for promoting better learning. Specific theories include:

- The cognitive constructivism perspective states that the learner relies upon cognitive processing for knowledge construction. Constructivist learning occurs when the learner has support to process the instructional materials available in a meaningful way (Chan & Black, 2006). In this case, the sense of touch could enable active discovery and represent a powerful teaching tool from a constructivist perspective (Minogue & Jones, 2006).

- The social cognitive theory states that students need to perform an active and proactive part in their learning (Harris et al., 2012). Haptic enhanced virtual environments could be designed to prompt active learning, by facilitating control of their learning and express their thinking.

- Dual-cognitive theory (DCT) proposes verbal and non-verbal encoding of information. Haptic feedback could be used as the source of the non-verbal stimuli (Jones, Minogue, Oppewal, et al., 2006).

- Cognitive-affective theory of learning (CATLM) with media extends on the cognitive theory of multimedia learning (CTML) by presenting the learner with resources other than words or pictures such as virtual reality media, case-based, and agent-based learning environments (Moreno & Mayer, 2007). This theory considers that: (i) learners use separate processing modalities to process different external modes, (ii) modality processing is limited by working memory capacity, (iii) new information has to be properly selected, organized, and integrated with prior knowledge to create meaningful learning, and (iv) cognitive engagement mediated by multimodal factors leads to meaningful learning (Schönborn et al., 2011).

- Embodied cognition suggests that conceptual learning can emerge from the knowledge acquired by the interaction of the body and the physical world. This perspective implies the physical activity is used as an anchor to comprehend abstract concepts (Han & Black, 2011). Here, sensorimotor interaction with the environment is closely related to the construction of knowledge (Bivall et al., 2011; Schönborn et al., 2011). Embodied cognition suggests that cognitive overload could be avoided by offloading the cognitive work onto the environment, which is now part of the cognitive system (Escobar-Castillejos et al., 2016). Haptic technology may allow embodied learning by facilitating movement embedded in the learning activity (Magana & Balachandran, 2017b). This theory was selected as the theoretical framework for the design of this research work learning environments, embodied cognition is covered in detail in chapter 3. This theory was selected given that it focuses on the belief that different kinds of sensorimotor experiences create different knowledge and understanding the same concept (Varela, Thompson, & Rosch, 2017). Thus, allowing us to differentiate visual- and touch-based learning activities, their combinations, and predominance levels. Additionally, this theory offers a way to ground abstract and complex concepts.

Although, there is theoretical backing to the inclusion of haptic technology in learning environments the empirical findings are conflicting (Yuksel et al., 2019; Zacharia, 2015).

2.4 Summary

This chapter provides an overview of the importance of addressing, from a research perspective, the learning of difficult concepts in science. Additionally, background information was provided regarding difficult concepts in physics, specifically buoyancy, and electricity and magnetism were addressed. The importance of the sense of touch is detailed along with haptic technology and interfaces. Finally, how haptic technology has been implemented in learning environments was also described.

CHAPTER 3. THEORETICAL FRAMEWORK

Successful learning is defined as a process that requires coordinated interaction of multiple cognitive processes comprising several brain networks. The mind constantly stores and summons information by structuring perceptions and experiences (National Academies of Sciences & Medicine, 2018). To create successful learning environments for abstract phenomena enhanced with haptic technology, the author selected Embodied Cognition Theory to guide the design of the learning experience.

3.1 Grounded Cognition

Traditional theories of cognition consider that knowledge is stored in a semantic memory system disconnected from the perception, introspection, and action modal systems. On the contrary, grounded cognition suggests that bodily states, modal simulations, and situated action are essential for cognition (Barsalou, 2008).

Abstract concepts can be represented using grounded theories. Even though, abstract concepts are not grounded to external sensory-motor representations. These theories adduce that bodily states are linked to cognitive activity, but they are necessarily crucial for cognitive processes. Meta-cognitive sources of knowledge are comparable to external sources when dealing with abstract phenomena (Barsalou, 2008).

Barsalou (2008) classified grounded theories into four categories: Cognitive linguistics theories, theories of situated action, cognitive simulation theories, and social simulation theories. Cognitive linguistic theories, such as cognitive semantics and cognitive approaches to grammar, advocate for the importance of embodied experiences, conceptual processes, and meaning in the study of language and its link with cognition (Evans, 2007). Theories situated in action exalt the role of perception and action in shaping cognition (Barsalou, 2008). Cognitive simulation theories, such as perceptual symbol systems and memory theories focus on the existence of a multimodal representation system that supports various cognitive processes (Barsalou, 2008). Social simulation theories explore the notion that an individual can simulate representations of other people's minds (Barsalou, 2008).

3.1.1 Embodied Cognition Theory

This theory emphasizes the necessity of dynamic, dynamic, and real interactions among the body and the real-world to create knowledge and generate conceptual learning (Zacharia, 2015). Under the perspective of embodied cognition, physical objects are important for connecting the abstract with the concrete (Bakker, Van Den Hoven, & Antle, 2011). Embodied knowledge on how materials or phenomena work is generated every time the body experiences them in the physical world (Zacharia, 2015). Furthermore, when learning new concepts, having related experiences provide perceptual grounding to the concepts (Black, 2010).

Applications of the effectiveness of embodied learning experiences have been evaluated in the context of spatial ability. Specifically, Burte, Gardony, Hutton, and Taylor (2017) stated that the use of embodied spatial training has a stronger effect on spatial thinking when compared with mental rotation practice. To foster spatial thinking using an embodied approach the researchers used physical folding/unfolding and cutting paper, the construction and interpretation of diagrams, and the use of pencil-and-paper for mental rotations. In a different study, Clifton et al. (2016) showed that there is an interaction between tangible and embodied interfaces (TEIs), systems' content, the spatial cognition engaged by the systems. TEIs incorporated sensing systems and physical objects allowing users to interact with digital information using their bodies. The researchers established a link between embodiment, intervention, and spatial cognition related to navigation, representation, and perception.

Embodied cognition also theorizes that cognition and linguistic processes in humans are grounded in physical interaction with their surrounding environment (Alibali & Nathan, 2012; Tran et al., 2017). Body systems mediate mental processes by using perceptual and physical interactions (Alibali & Nathan, 2012; Burte et al., 2017). Perceptual and motor systems are fundamental for concept definition and interpretation (Anderson, 2003). In other words, the mind is intrinsically embodied because cognition depends on the body's limitations and capabilities (Alibali & Nathan, 2012). The details of the individual's embodiment (abilities, physical characteristics, activity) provide the structure of the individual's reasoning (Anderson, 2003). Figure 3.1 represents a taxonomic classification of embodiment (Goldman & de Vignemont, 2009). Bodily formats are used to code interoceptive and directive representations of the individual's actions or bodily states. Each perceptual modality may use a distinctive code or a set of unique codes (Goldman & de Vignemont, 2009).

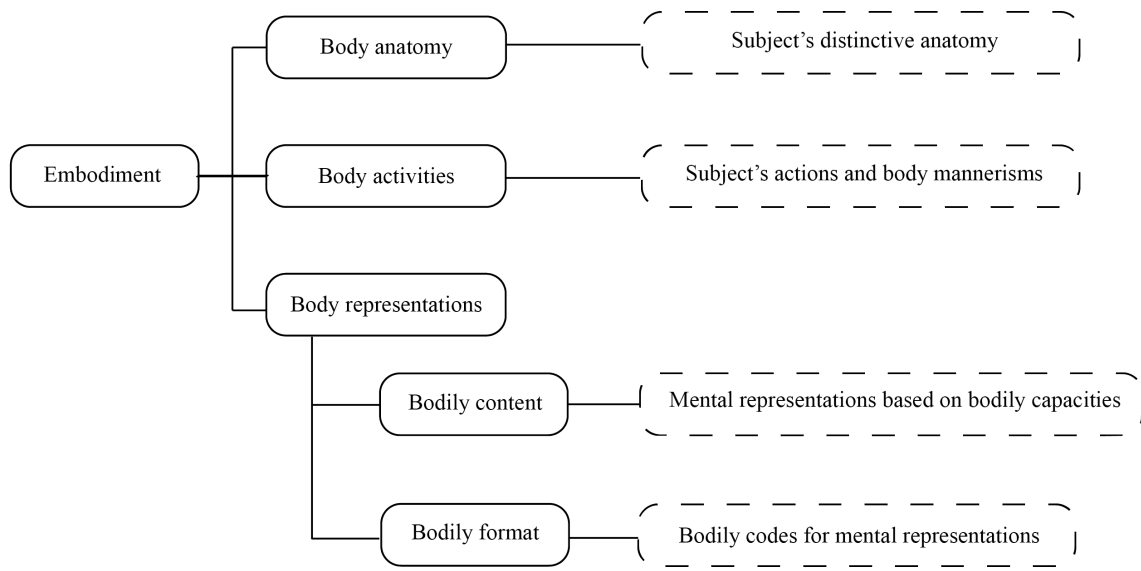


Figure 3.1. Embodiment taxonomy (Goldman & de Vignemont, 2009).

Body movements/actions afford divergent learning channels that could be used to understand learning materials or difficult concepts (Chao, Huang, Fang, & Chen, 2013). The experiences derived from the body sensorimotor capabilities are in essence embodied cognition (Shapiro, 2010). Perceptual events create perceptual cognitions which are coupled with motoric cognitions forming embodied cognitions (Goldman & de Vignemont, 2009). Even *offline* cognition, cognition that happens in the absence of environmental inputs, is established by perception and action (Alibali & Nathan, 2012). Mental imagery, reading comprehension, construction of mental models while reasoning, and reproduction of actions while comprehending language are examples of cognitive tasks that use the motor and sensory resources, even if the reference tasks are inaccessible (Alibali & Nathan, 2012).

Cognition in real-world environments provides the opportunity of handling and interacting with manipulatives (Alibali & Nathan, 2012); physical manipulation and activity are critical in learning and development (Bakker et al., 2011). Grounding learning experiences create a link between abstract concepts and a concrete object or experience. Strong and transferable knowledge is created by physical and perceptual grounding (Alibali & Nathan, 2012). For instance, Bakker et al. (2011) developed physical artifacts (MoSo Tangibles) that children could interact and manipulate the tempo, tone, volume of ongoing sounds. The MoSo tangibles were designed using embodied metaphors as a foundation. The results showed that participants mostly used verbal expressions to explain volume, pitch, and tempo. The researches pointed out that the gestures and movements used by participants to support their verbalization were related to the artifacts used. Finally, the researchers concluded that tangible interactions can be used to create embodied metaphor-based systems.

Phenomena that are imaginary, impossible or difficult to experience can be simulated by using equivalent metaphors or analogies of their physical environments (Alibali & Nathan, 2012). Embodied metaphors are constructed interactively by mapping physical activity with abstract concepts (Bakker et al., 2011). Alibali and Nathan (2012) stated that mathematical cognition is embodied because it is “grounded in the physical environment”[p.247] and “based in perception and action”[p.247]. From the embodied cognition view, representational gestures are the manifestation of perceptual and motoric simulations underlining language. In the physical environment pointing gestures are the representation of grounding of cognition, metaphoric gestures show that metaphors ground in the body (Barsalou, 2008). Abrahamson and Lindgren (2014), suggested that conceptual reasoning is created by physical interactions. For example, cognitively, the utilization of symbolic notation is similar to the manipulation of objects in space.

Teaching and learning are multimodal interactions that take place in informative environments and depend on cultural background, prior knowledge, and resources (Alibali & Nathan, 2012). Learning experiences become more meaningful for students when touch and physical movement is incorporated (Chao et al., 2013). For example, Black (2010) determined that direct manipulation via forced feedback of a gears’ simulation enhanced problem-solving skills and memory. Also, Chao et al. (2013) used a Kinect device to create embodied cognition connecting the physical environment and mental representations. The researchers' results supported the importance of embodied cognition in recalling of action phrases and also showed that technology-mediated cognitive processing is effective.

3.1.2 Embodied Cognition to Support Learning with Visuohaptic Simulations

Sensory feedback generate unique metaphorical projections of schemata for abstract concepts (Zacharia, 2015). Embodied cognition rests on the creation of multimodal representations to generate conceptual understanding (Zacharia, 2015). To support complex concept understanding the utilization of different sensory modalities enables richer multimodal representations (Zacharia, 2015). The implications of embodied cognition theory for the design of learning environments should consider two fundamental elements. One is the level of embodiment and the second one is design principles for designing learning environments that can effectively promote embodied learning. Regarding the level of embodiment, Tran et al. (2017) proposed a degree of embodiment classification based on motoric engagement, gestural congruency, and immersion (Figure 3.2). Motoric engagement is defined as the level of use of the motor system (Johnson-Glenberg et al., 2014; Tran et al., 2017). Johnson-Glenberg et al. (2014) links high motoric engagement with locomotion, the continuous movement also affects the use flow of the environment (Johnson-Glenberg et al., 2014). The degree of gestural congruency is determined by how well-mapped content is to gestures (Johnson-Glenberg et al., 2014). Immersion is constructed by sensomotoric, social, emotional, and temporal factors (Pietschmann, Valtin, & Ohler, 2012). To determine the level of embodiment sensomotoric immersion should be considered, created by the interaction of the user and the system interface (Pietschmann et al., 2012).

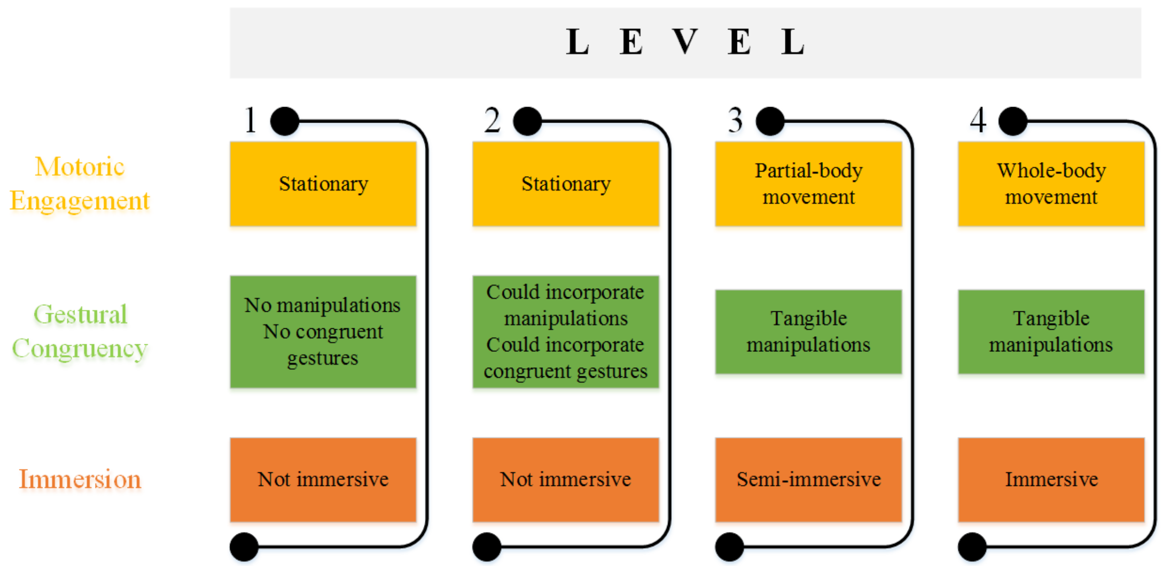


Figure 3.2. Degree of embodiment: Level 1 represents the lowest level of embodiment achievable, on the other hand, level 4 is the highest level (Johnson-Glenberg et al., 2014; Tran et al., 2017).

Once the level of embodiment is defined, the second consideration relates to defining how embodied learning will be promoted. Smith and Gasser (2005) recommended that an embodied activity should possess the following characteristics: be multimodal, be incremental, be physical, enable exploration, learn a language, and be social. On the other hand, Abrahamson and Lindgren (2014) identified several principles for designing embodied learning experiences. These guidelines focus on the activity, materials, and facilitation of an optimal embodied experience:

1. Learning activity

    - Symbolic stimuli should be minimized or discard on favor of graphical, figurative, iconic, or diagrammatic representations.
    - The activity should enable perceptual sensory exploration and/or kinesthetic orientation.
    - Start with simple tasks that build up in complexity over time.

2. Materials

    - Participants must understand the purpose of the facilitating agents used in the learning environment.
    - The learning environment needs to provide feedback for participants' somatic actions.
    - Computer-based learning environments should allow exploration throughout the manipulation.
    - Equipment configuration should be flexible and adjust the learning environment objectives, which could change over time.

3. Facilitation

    - Integrate cues to guide optimal body movement.
    - Transmit expert's perspectives onto participants. The instructor can use multimedia presentations, hand-on coaching, demonstrations, etc.
    - Prompt participants to describe their interaction with the materials and learning environment.

3.1.2.1 Embodied learning interventions: Electricity and Magnetism, and Buoyancy

To test the research questions that guided this work, refer to Section 1.4, two experiments were implemented using embodied cognition as a framework: Electricity and Magnetism, and Buoyancy. The learning tasks in these experiments are either inquiry-based or hands-on, both prompting active engagement in the learning environment (Yuksel et al., 2019). Inquiry-based task allows analysis, assessment, revision, and revision of the concepts under study (Yuksel et al., 2019). Hands-on tasks support the understanding of abstract concepts by anchoring them to tangible experiences (Yuksel et al., 2019).

For the *Electricity and Magnetism*, a computer-based simulation was used, this simulation allowed visual and/or haptic feedback. This simulation presented three systems that could be explored: point, lane, and ring. The simulation used graphical representations to depict each system. Participants navigated the environment staring with the point system, easier system, then the infinite lane system, and finish with the ring system (hardest system). Activities completed at each stage integrated guidance on how to interact with the simulation. Experts' perspective was included by the utilization of isosurfaces and force vectors. Assessments instructed participants to describe what they had experienced during the learning activity, drawings or words could be used.

In the *Buoyancy* experiments, two embodied learning environments were implemented. The hands-on environment used different fluids and objects for experimentation. Contrarily, the visuo-haptic simulation allowed the user to change the object size and fluid density. Booth environments encouraged hand, wrist, and arm locomotion. Participants work through tasks that focused on changes on the densities of the objects and where asked to explain what happened and why.

3.2 Summary

This chapter addresses Embodied Cognition Theory definition, related concepts, and its link to multimodal learning environments enhanced by haptic technology. It also describes how principles of embodied learning design were used for the design of the learning interventions tested as part of this study.

Table 3.1. Design principles for Electricity and Magnetism, and Buoyancy

Embodiment Design Principle	Electricity and Magnetism	Buoyancy
Learning Activity		
Symbolic representations	Use of graphical representations on visuo-haptic simulation.	Use of graphical representations on visuo-haptic simulation. Use of physical manupulatives on hands-on activity.
Sensory exploration	Visual and touch stimuli available.	Visuohaptic: Visual and touch stimuli available, Hands-on: All senses involved.
Complexity build up	Tasks start with a point, then line, and finally ring simulations.	Task start with equal fluid and object densities, then the liquid density is changed. Finally the object density is changed.
Materials		
Agents purpose	PowerPoint presentation	PowerPoint presentation
Feedback	Visual and force feedback	Visual, tactile, and force feedback.
Exploration	Probing	Probing and hands-on
Equipment configuration	Menu on simulation	Menu on simulation, objects and fluids re-utilization.
Facilitation		
Movement cues	Not provided	Not provided
Experts perspective	3D capabilities, isosurfaces, and force vectors.	Not provided
Description	Draw force system, explain the phenomena	Draw force system, explain the phenomena

CHAPTER 4. EXPERIMENTS AND RESULTS ELECTRICITY AND MAGNETISM

4.1 Learning Design

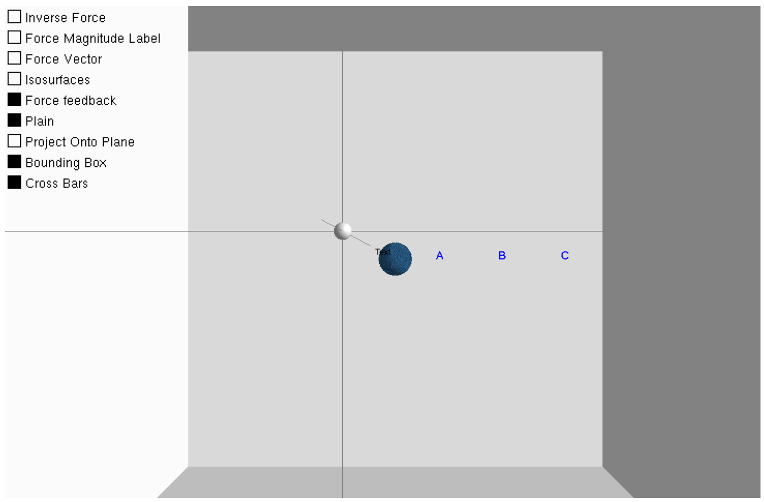
This section identifies the learning objectives of the lesson where students learned about electricity and magnetism with visuo-haptic simulations. This section also describes the visuo-haptic simulation along with its affordances for learning and instructional supports. Also, this section describes how the principles for embodied design were embedded within this intervention.

4.1.1 The visuo-haptic simulation

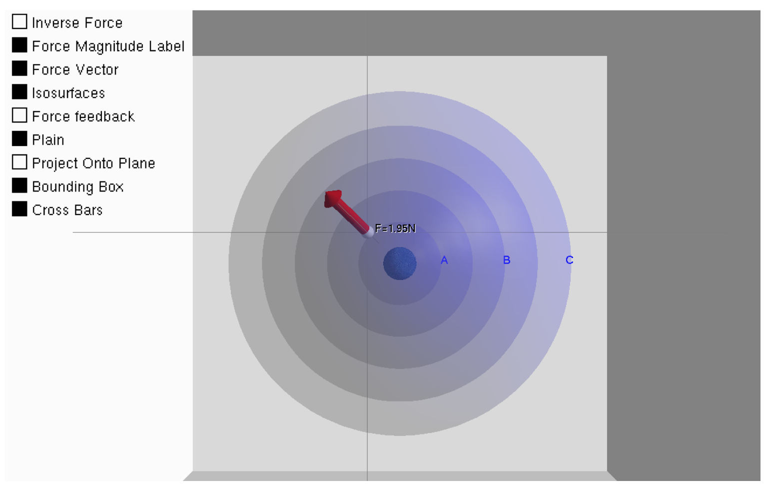
The learning environment simulated the electric fields around a point, an infinitely long line, and ring charges. The simulation incorporated 3D capabilities, which were explored using the haptic device. The same learning environment was used for all treatment groups (See Section 4.2.2), and students were able to interact with the visuo-haptic simulation, which afforded the following forms of visual and haptic feedback:

- Inverse force: when activated, the charge changes to a negative electric charge.
- Force magnitude label: When activated, the magnitude of the force is shown in newtons.
- Force vector: If activated, the direction of the force is shown as a vector.
- Isosurfaces: after activation, a visualization of the field's propagation in a volume appears.
- Force feedback: Enables the haptic force feedback.

- Plain: When activated it, deactivates force magnitude level, a force vector, and isosurfaces.
- Project onto plain and bounding box: Control the background 3D representation.
- Crossbars: It activates auxiliary lines for the charge.



(a)



(b)

Figure 4.1. Treatment A and B for Electricity and Magnetism I, point charge simulation: (a) Haptic-enhanced with minimal visual cues (H1), and (b) visually-enhanced only with no haptic feedback (V1).

Visual and haptic feedback (see Figure 4.1(a) and 4.1(b)) were configured in different forms and for different treatment groups. The treatment groups were: haptically-enhanced only with minimal visual cues, rich visually-enhanced cues only, and the combined version of haptically-enhanced with rich visually-enhanced cues. Haptically-enhanced only with minimal visual cues (H1) used only the force feedback, plain, bounding bars, and crossbars options (Figure 4.1(a)). On the other hand, the rich visually-enhanced cues only (V1, V2, V3, V4, and V5) simulation used force magnitude label, force vectors, isosurfaces, bounding box, and cross bars (Figure 4.1(b)). The haptically-enhanced with rich visually-enhanced cues used both, either simultaneously (V+H) or sequentially (H $\rightarrow$ V+H).

4.1.2 The haptic device

The force feedback stimuli were delivered by a Novint Falcon device, which is the first commercially available haptic device that can provide three degrees of freedom (3 DoF), force feedback, and also be used as a 3D input or output mechanism (HapticsHouse.com, 2017; Rodríguez & Velázquez, 2012).

The Novint Falcon uses a translational only variation of a delta-robot configuration (Karbasizadeh, Aflakiyan, Zarei, Masouleh, & Kalhor, 2016; Martin & Hillier, 2009). Karbasizadeh et al. (2016) stated that the parallel architecture of the delta-robot configuration offers higher acceleration, speed, stiffness, and payload capability when compared with serial architecture. This apparatus has an interchangeable end-effector that allows a pistol grip, pen-holder, and a gripper (Martin & Hillier, 2009).

A USB interface is used to send and receive the controlling commands that provide actuation in the form of sensory data (Martin & Hillier, 2009). To render force feedback, the Falcon transmits a position and the system answers with force vector which is achieved by supplying current to the servomotors (Rodríguez & Velázquez, 2012).

The device utilizes three Mabuchi RS-555PH-15280 coupled to a drum (Martin & Hillier, 2009). Rodríguez and Velázquez (2012) described that the device provides 400 dots per inch (dpi) for resolution, nine Newtons (N) for force, and one kilo Herts (kHz) update rate for the position-force loop.

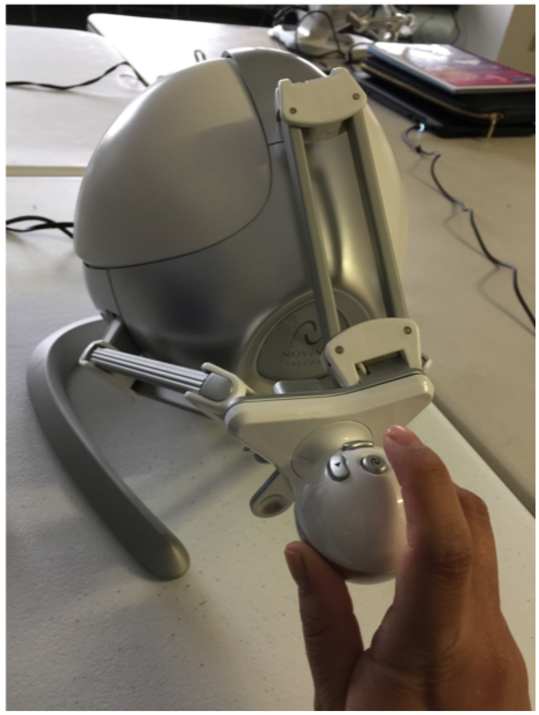


Figure 4.2. Novint Falcon device.

4.1.3 The worksheet

The worksheet for rich visual treatments and haptic enhanced treatments had the objective of guide participants' interaction with the visuao-haptic simulation, and to elicit participants' reflection about the tasks on hand. The goal of the worksheet was to teach about electric forces using the point, infinite line, and ring charges simulations to test charge changes based on distance.

4.1.3.1 Embodied design principles

Charges were explored based on level difficulty, starting with the easier interaction the point charge, continuing with the line charge, and finalizing with the ring charge simulation. Students use visual and/or touch stimuli to interact with the visuo-haptic simulation and use the new information to complete the worksheet. The simulation use graphical representation for most of the concepts displayed, only the force was represented symbolically. In the worksheet students start by proving the change with the haptic device, in the case of visual treatments the haptic device was only used as a 3D mouse, the students were instructed to position the prove on different distances.

The visuo-haptic simulation, assessments, and worksheets were used as materials for the electricity and magnetism learning environment. The worksheets provide instructions on the order in which participants should interact with each charge. Participants in the haptic enhanced groups receive and provide feedback using the haptic device. Additionally, participants can enable or disable menu options using the computer trackpad. Participants on the control treatments (V1-5) use the haptic device as a mouse and receive feedback via visual cues, the trackpad can also be used to change menu options. Patters of the movement were not provided participants were led free use movements that they believe were fit for completing the learning tasks. A series of open-ended questions were used in the worksheet to explore change on strength of force with distance and the force direction. To answer the open-ended questions participants could use drawings or symbolic representations.

4.2 Research Design

This research used a quasi-experimental design, sections were already formed but treatments were randomized per section, to detect stimuli conditions under which participants improved their conceptual knowledge of charges behavior. In this section, we define the methods used to address the research problem. Quantitative and qualitative methods were used to answer the research questions.

4.2.1 Research questions and hypotheses

The experiments were designed to answer the following research questions:

1. Does the addition of tactile stimulus to an electricity and magnetism computer-based simulation affect the conceptual knowledge about the subject?

H_{o1}: The availability of tactile stimulus has no effect on final conceptual knowledge about Electricity and Magnetism.

H_{a1}: The availability of tactile stimulus will affect the final conceptual knowledge about Electricity and Magnetism.

2. Does the modality (single, dual, sequenced) in which tactile and visual feedback is delivered affect students' development of conceptual learning of electricity and magnetism concepts?

   H_{o2}: The type of learning modality used for interaction by students has no effect on their final conceptual knowledge about Electricity and Magnetism.

   H_{a2}: The type of learning modality used for interaction by students will affect their final conceptual knowledge about Electricity and Magnetism.

3. How does the interaction with a visuo-haptic simulation influence scientific conceptualization of electricity and magnetism?

4.2.2 Treatment conditions

A total of five experiments were conducted during Spring 2016, Fall 2016, Spring 2017, Fall 2017, and Spring 2018. Each experiment explored a different modality of visual and haptic feedback. Single modalities (Visually-enhanced only with no haptic feedback) were used as the control group (Treatment B) for all experiments. Table 4.1 provides a summary of the experiments. As an experimental group (Treatment A) the following modalities were used:

- Electricity and Magnetism I: Single modality was implemented of the haptic enhanced learning environment with minimal visual cues (H1). minimal visual cues.
- Electricity and Magnetism II, III, and V: Sequenced modality was used as a learning environment with haptic enhancement and minimal visual cues were followed by visual cues activation (H $\rightarrow$ H+V).

- Electricity and Magnetism IV: Simultaneous modality was implemented using haptic and visual cues at the same time (H+V).

Table 4.1. Electricity and Magnetism experiments and respective treatments

Experiment	N	Academic Period	Treatment A	Treatment B
I	41	Spring 2016	Haptic-enhanced only with minimal visual cues (**H1**)	Visually-enhanced only with no haptic feedback (**V1**)
II	43	Fall 2016	Haptic-enhanced only with minimal visual cues followed by visual cues activation (**H2 → H2+V2**)	Visually-enhanced only with no haptic feedback (**V2**)
III	38	Spring 2017	Haptic-enhanced only with minimal visual cues followed by visual cues activation (**H3 → H3+V3**)	Visually-enhanced only with no haptic feedback (**V3**)
IV	57	Fall 2017	Visually-enhanced and haptic feedback (**H4+V4**)	Visually-enhanced only with no haptic feedback (**V4**)
V	31	Spring 2018	Haptic-enhanced only with minimal visual cues followed by visual cues activation (**H5 → H5+V5**)	Visually-enhanced only with no haptic feedback (**V5**)

4.2.3 Context and participants

Participants were undergraduate students from a class of physics for elementary education majors. Experiments were performed in Spring 2016, Fall2016, Spring 2017, Fall 2017, and Spring 2018 semesters. Details regarding the number of participants assigned to each treatment condition are represented in Table 4.2.

Table 4.2. The number of participants per treatment in the Electricity and Magnetism experiments.

Experiment	Academic Period	Treatment A	Treatment B	Total
Electricity and Magnetism I	Spring 2016	20	21	41
Electricity and Magnetism II	Fall 2016	23	20	43
Electricity and Magnetism III	Spring 2017	16	22	38
Electricity and Magnetism IV	Fall 2017	25	32	57
Electricity and Magnetism V	Spring 2018	20	11	31

Students were enrolled in *PHYS 215: Physics for Elementary Education* offered at Purdue University West Lafayette campus. The course focuses on the content and nature of science materials. The course content and experiments were delivered and conducted by the same faculty member. The research experiments were adapted to be incorporated as part of the regular curriculum.

Experiments were carried out in the Research on Computing in Engineering and Technology Education (ROCkETEd) haptics laboratory. Each student worked individually in a separate station (Figure 4.3). The laboratory allowed us to accommodate 18 participants at a time. The course offered two sessions each semester, due to workspace limitations each session was divided in half. Treatments were assigned randomly to each half session. PHYS 215 was selected because of its focus on developing deep conceptual understanding by creating creative and understandable learning processes.

A total of 210 students participated in all five experiments. Participants in *Electricity and Magnetism I* indicated that 80.49% (41) were enrolled in Elementary Education, 17.07% (7) Special Education, and 2.44% (1) Linguistics as their academic major. The academic level was 12.2% (5) freshman, 7.32% (3) sophomore, 24.39% (10) junior, and 56.10% (23) senior. A total of 48.78% (20) reported taking high school physics courses and none of the participants participated in undergraduate physics courses before. In *Electricity and Magnetism II* the most reported academic major was Elementary Education with 74.42% (32), followed by Special Education with 13.95% (6), 9.30% Early Childhood Education and Exceptional Needs, and 2.33% (1) undecided. The academic level of participants was 4.65% (2) freshman, 46.51% (20) sophomore, 39.53% (17) junior, and 9.30% (4) senior. A 39.53% (17) reported that did not take any high school physics classes,

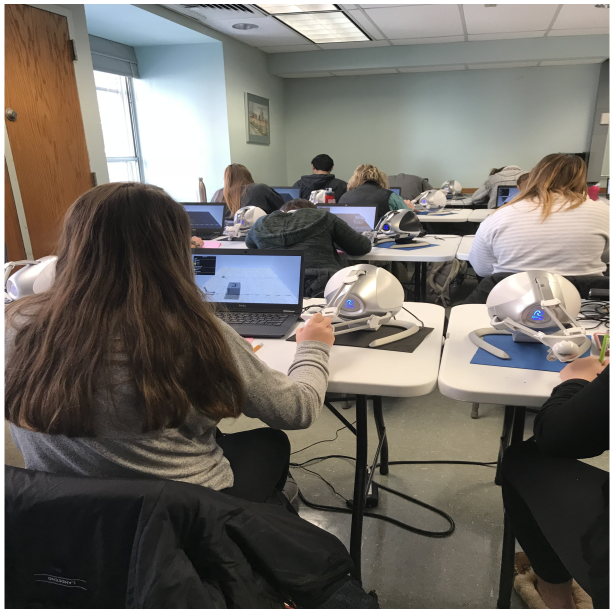


Figure 4.3. Research on Computing in Engineering and Technology Education haptic laboratory.

20.93% (9) did not respond, and 39.53% (17) took physics courses in high school. Finally, 79.07% (34) of the students did not take any physics course previously and 20.93% did not respond. *Electricity and Magnetism IV* reported the following major distribution: 70.18% (40) Elementary Education, 21.05% (12) Special Education, 5.26% (3) Early Childhood Education and Exceptional Needs, 1.75% (1) Finance, and 1.75% Exploratory Studies. Participants were 91.23% (52) females and 8.77% (5) males. Participants were 5.26% (3) freshman, 43.86% (25) sophomore, 36.84% (21) junior, and 14.04% (8) senior students. A total of 63.16% (36) took physics courses in high school and 36.84% (21) did not. Finally, only 3.51% (2) took undergraduate physics classes before. In *Electricity and Magnetism V* 67.74% (21) reported Elementary Education as their major, 12.90% (4) declared Special education, 3.23% (1) from Computer and Information Technology, and 16.13% did not respond. Students were 6.45% (2) freshman, 58.06% (18) sophomore, 16.13% (5) junior, 3.23% (1) senior, and 16.13% did not respond. A total of 80.65% (25) identified themselves as female, 3.23 (1) as male, and 16.13% did not respond. Students that had taken high school physics curses corresponded to 35.48% (11), 48.39% (15) did not take any classes, and 16.13% did not respond. Finally, 83. 87% of the participants did not take undergraduate physics classes before and 16.13% did not respond.

4.2.4 Procedures

Electricity and Magnetism I explored the use of single modality learning environments (Figure 4.4). In *Electricity and Magnetism II, III, and V* the experimental group (Treatment A) was exposed to a sequenced approach to haptic and visual stimuli (Figure 4.5). Finally, *Electricity and Magnetism IV* implemented a simultaneous stimulus learning activity (Figure 4.6). Additionally, experiments I, II, and IV filled out a delayed post-test and a delayed transfer test two weeks after the interaction with the Electricity and Magnetism learning environment.

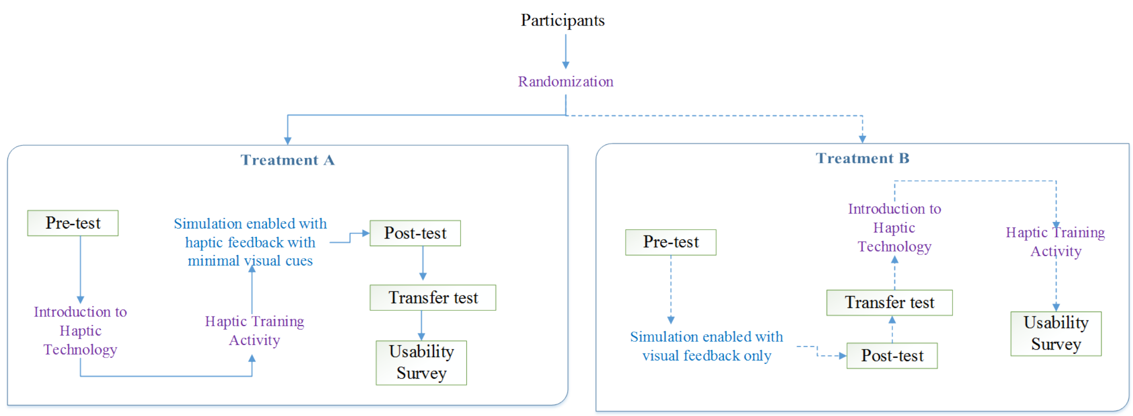


Figure 4.4. Electricity and Magnetism I: single modality experiment procedure.

Participants within each of the control groups (V1, V2, V3, V4, and V5) had the opportunity of interacting with force feedback after all the assessments related to electricity and magnetism were collected.

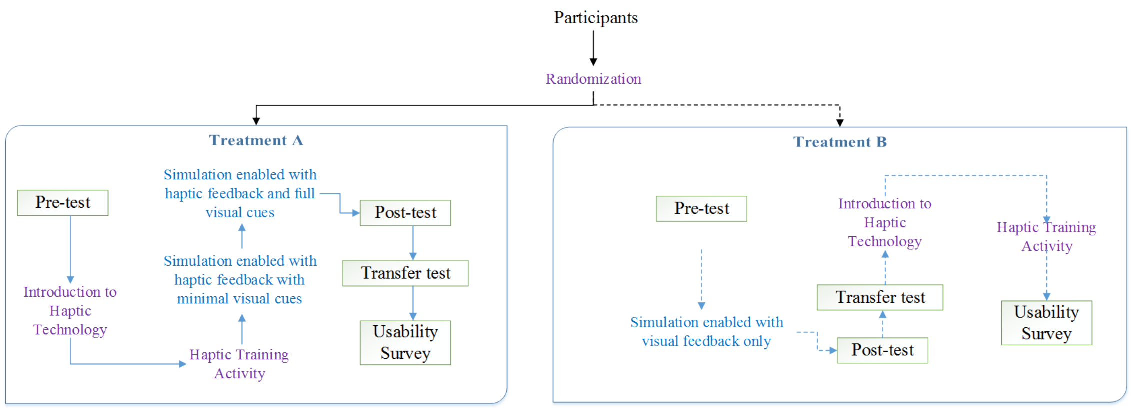


Figure 4.5. Electricity and Magnetism II, III, and V: sequenced modality experiment procedure.

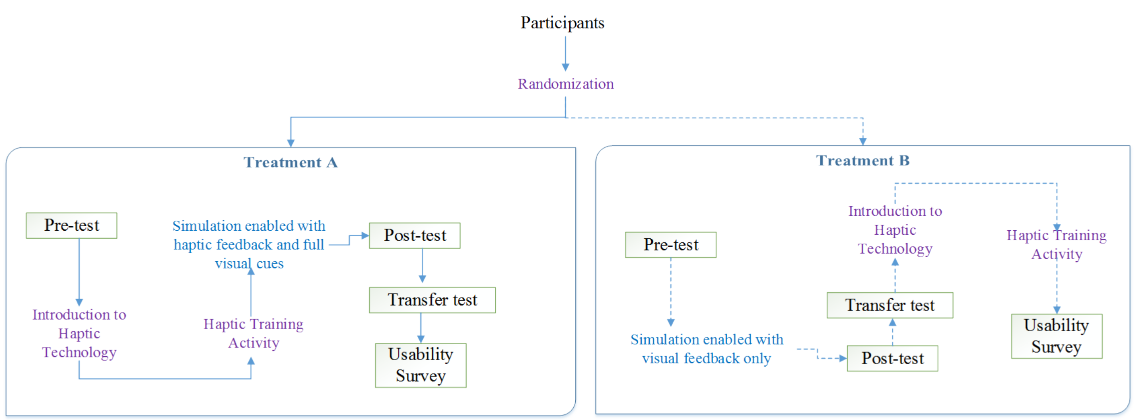


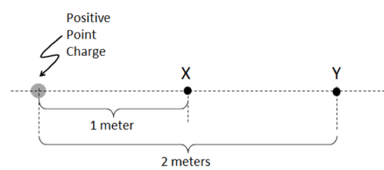
Figure 4.6. Electricity and Magnetism IV: simultaneous modality experiment procedure.

4.2.5 Data collection method

The data was collected using questionnaires that were administrated using paper and pencil. For the *Electricity and Magnetism*, experiments two assessments and two worksheets were created. The assessments details are listed below:

- Pre-test, post-test, and delayed post-test: This assessment had two iterations. The first one was used in experiments I, II, and II, it contained eight multiple-choice questions and one open-ended question (please refer to Annex A.1). The second iteration was the one used for IV and V and contained five multiple-choice questions and one open-ended question (Annex A.2). Five of the questions came from the first version and one from the transfer test first version. The following questions are examples of the assessments content:

    1. A **positive point charge** is shown below. How does the electrical force on a positive test charge placed at Y (2 meters away) compare with the electrical force on the same positive test charge if it were placed at X (1 meter away)?

        (a) Force on test charge placed at Y is **FOUR TIMES** the force on test charge placed at X.

        (b) Force on test charge placed at Y is **TWICE** the force on test charge placed at X.

        (c) Force on test charge placed at Y is **EQUAL TO** the force on test charge placed at X.

        (d) Force on test charge placed at Y is **ONE HALF** the force on test charge placed at X.

        (e) Force on test charge placed at Y is **ONE FOURTH** the force on test charge placed at X.

       (Magana, Serrano, & Rebello, 2019)

    2. In the figure, positive charges q2 and q3 exert on charge q1 a net electric force that points along the +x axis. If a positive charge Q is added at (b,0), what now will happen to the force on q1? (All charges are fixed at their location).

(a) No change in the size of the net force since Q is on the x-axis.

(b) The size of the net force will change but not the direction.

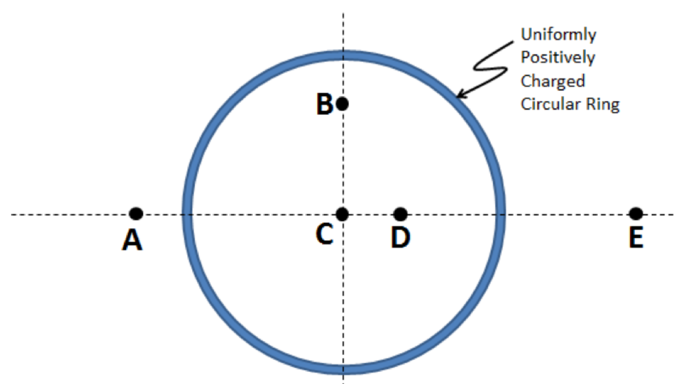
(c) The net force will decrease and the direction may change because of the interaction between Q and the positive charges q2 and q3.

(d) The net force will increase and the direction may change because of the interaction between Q and the positive charges q2 and q3.

(e) Cannot determine without knowing the magnitude of q1 and/or Q.

(Maloney, OKuma, Hieggelke, & Van Heuvelen, 2001)

3. A **uniformly positively charged ring** is shown below. Draw arrows representing the force experienced by a **positive test charge placed** at points **A, B, C, D, and E**. The direction of each arrow should represent the direction of the force. The length of each arrow should represent the strength of the force at that point.



(Magana et al., 2019)

Additionally, the pre-test contained the following demographic questions:

1. Please indicate your academic major at Purdue
   (a) Elementary Education
   (b) Other:
2. Please indicate your academic level:
   (a) Freshman
   (b) Sophomore
   (c) Junior
   (d) Senior
   (e) Graduate Student
      i. Master
      ii. PhD
3. Please rate each statement below on the scale provided by circling your choice:

Table 4.3. Demographic multiple-choice questions Buoyancy pre-test

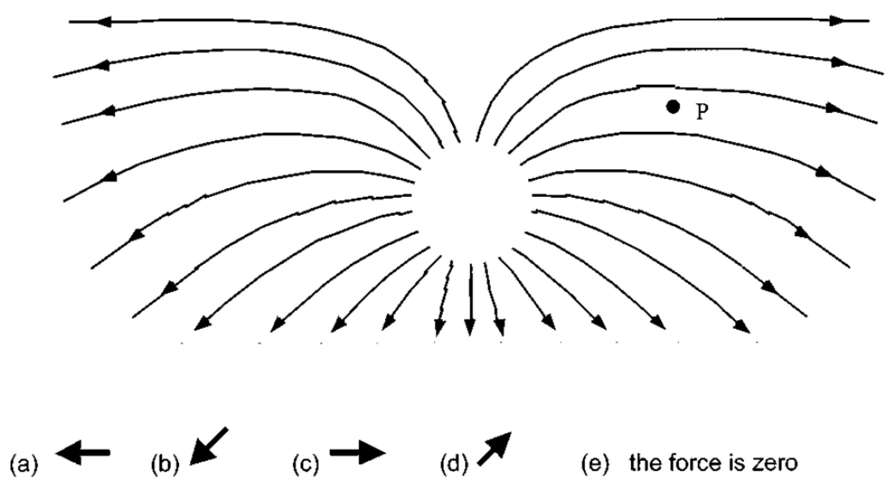
Question
I feel confident about my understanding of physics concepts
I feel confident about my understanding of electric charges
I know about haptic technology
I have a strong liking for physics

   The participants used a five-point Likert scale to answer this question (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree).

4. Please list any **high school physics courses** you have taken. If you have not taken any high school physics courses, please write None
5. Please list any **undergraduate physics courses** you have taken, prior to this course. If you have not taken any prior undergraduate physics courses, please write None

- Transfer and delayed transfer test: The transfer survey was designed to determine if the activity altered the performance of participants in other electrostatics concepts besides charge behavior. Two versions of this assessment were used. The first version, applied on Electricity and Magnetism I, II, and III. This test version contained 10 multiple-choice questions (refer to Appendix A). The second version was built for experiments IV and V. This version contained eight multiple-choice questions from the original survey and three questions from the original version of the pre/post/delayed post-test. The following questions are examples of the assessment content:

    1. What is the direction of electric force on a negative charge at point P in the diagram below?

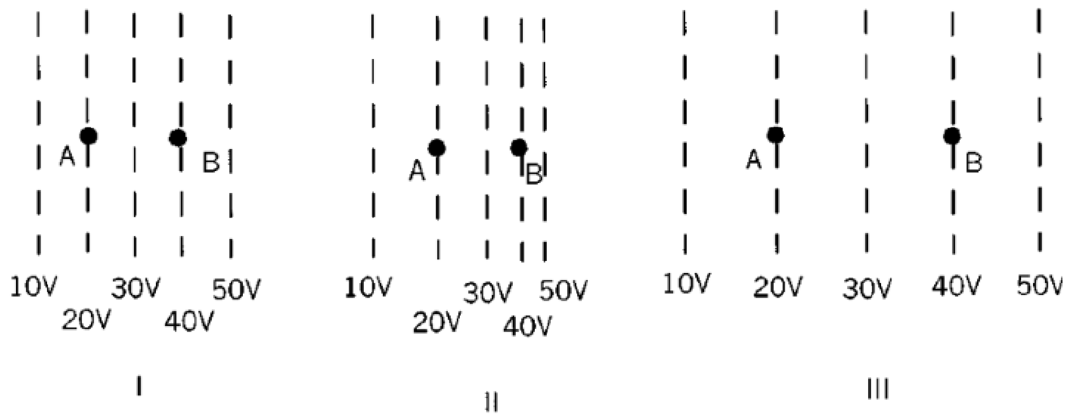
        (Maloney et al., 2001)

    2. In the figures below, the dotted lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) How does the magnitude of electric field at B compare for these three cases?

        (a) I $>$ III $>$ II

        (b) I $>$ II $>$ III

        (c) III $>$ I $>$ II



(d) II > I > III

(e) I = II = III

(Maloney et al., 2001)

- Haptic usability survey: The usability survey contained five multiple-choice questions and used a five-point Likert scale (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree) to collect responses. Additionally, the survey contained one open-ended question which aimed to collect students' perceptions of the utilization of haptic technology for learning scientific concepts. The questions are detailed in Table 4.4.

Table 4.4. Haptics usability survey questions

Number	Question	Type
1	I enjoyed learning physics concepts with haptic devices.	Multiple-choice
2	Haptic devices were easy to interact with.	Multiple-choice
3	It was easy to interpret the force feedback provided by the haptic device.	Multiple-choice
4	Interacting with haptic devices requires a lot of mental effort.	Multiple-choice
5	Interpreting the force feedback requires a lot of mental effort.	Multiple-choice
6	Please provide any comments or observations about the use of haptic technology for learning science concepts:	Open-ended

- Worksheet: The same worksheet was used for both treatments. The worksheet guided the students throughout the three simulations:
  - Point charge: Participants were able to test charges at different distances (Figure 4.7(b)).
  - Infinitely long line of charge: Participants experienced simulated electric force on charges at different distances (Figure 4.7(a)).
  - Ring of charge: Participants tested charge changes with distance both inside and outside the ring (Figure 4.7(c)).

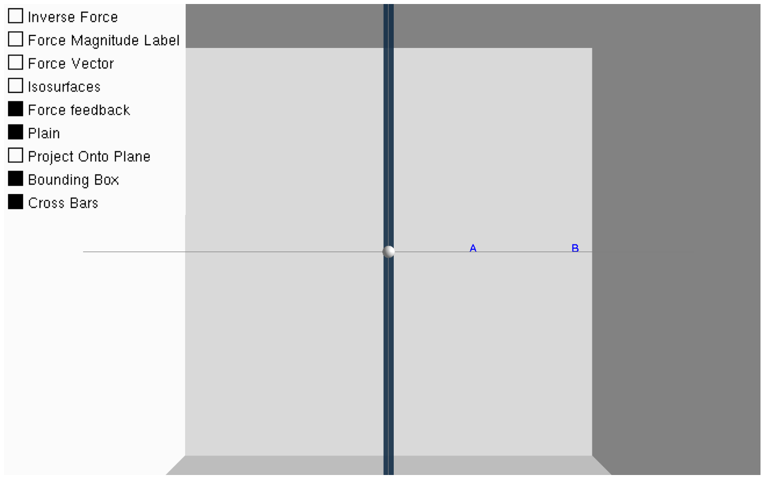
  Additionally, two multiple-choice questions were presented at the end of the worksheet to assess the participant's confidence in the provided answers and perceived usefulness of the worksheet. The detailed worksheet is available in Appendix A.
  Visuohaptic and hands-on worksheets only difference was that instead of the word "feel" the word "see" was used.

4.2.6 Data analysis method

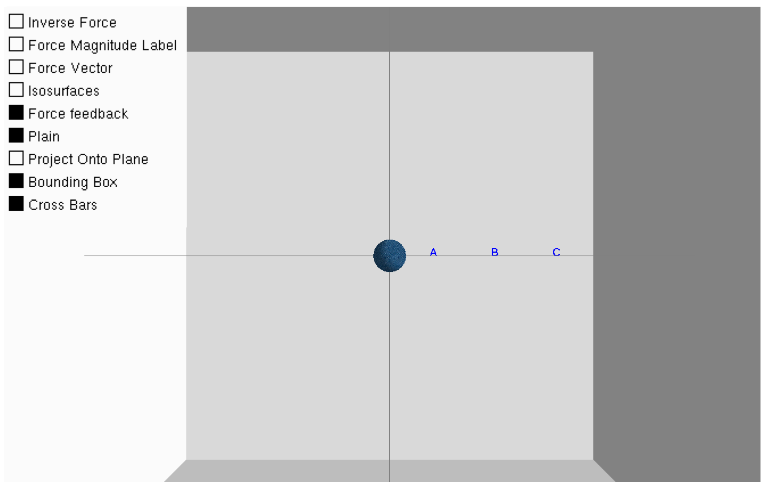
Only participants who completed the entire research procedures were considered for analysis, 16 participants were excluded from the data pool. Before the analysis was carried out, the researcher proceeded to transcribe the responses. Then, a code was assigned to each participant to anonymize the data.

4.2.6.1 Quantitative analysis

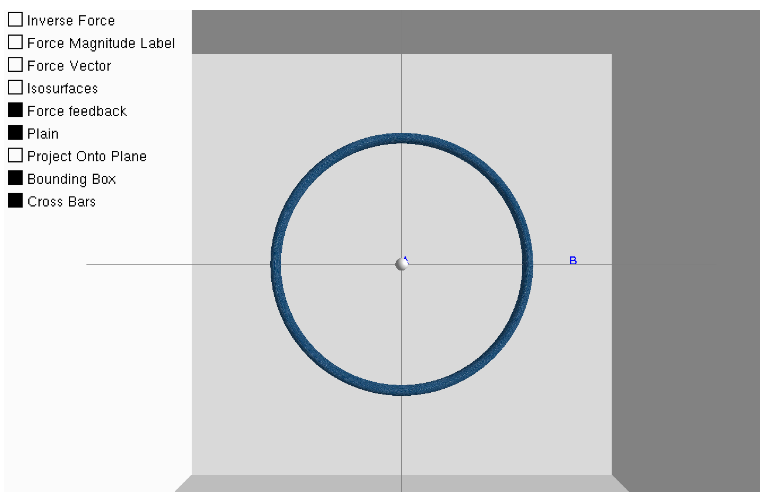
The quantitative analysis focused on the study of multiple-choice questions from pre-test, post-test, delayed post-test (if available), transfer test, and delayed transfer test (if available). The transcribed responses were scored with one (1) point if correct and zero (0) if incorrect. For the statistical analysis of pre-test, post-test, delayed post-test (if available) scores only questions one to four from the second assessment version were considered.



(a)



(b)



(c)

Figure 4.7. Electricity and Magnetism I, haptically-enhanced with minimal visual cues (H1): (a) infinitely long line of charge, (b) point charge, and (c) ring charge.

Descriptive statistics were obtained for all experiments. To answer the research question regarding the effect of tactile stimulus in the subjects' conceptual knowledge regarding electricity and magnetism (refer to Section 4.2 research question one) a one-way ANOVA was applied to the Treatment A and B pre-test scores to determine if the treatment groups were comparable. Since the samples were comparable, the researcher proceeded to conduct a paired t-test to contrast scores within treatments to determine if there was a significant difference between data collections of the same treatment, followed by a two-sample t-test to compare the post-test scores. A two-sample t-test was also applied to the transfer data and if there was a delayed data collection, a paired t-test was conducted.

To address the research question concerning to the use of different modalities, refer to Section 4.2 question two, the researcher first conducted a one-way ANOVA using the pre-test scores to determine if the treatment groups were comparable between experiments. Treatments with the same conditions were grouped if they were statistically similar. The grouped treatments were then subjected to a one-way ANOVA using the post-test scores to find differences between treatments. Only four experiments collected delayed post-test data (Electricity and Magnetism I, II, and IV) a Nested Factorial analysis was conducted to compare the effect of each treatment on the pre-test, mid-test, and post-test scores. The nested factorial model used for the analysis was:

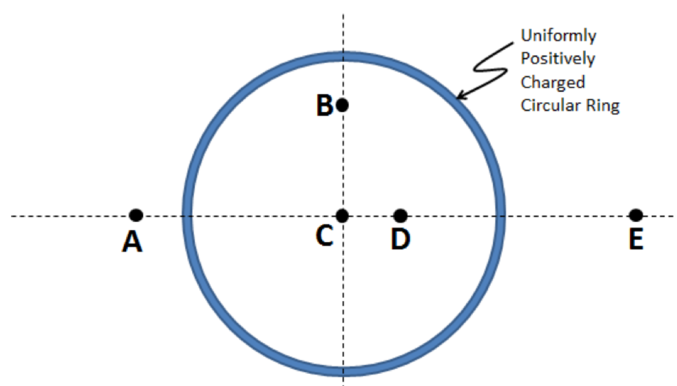
$$S_{ijkl} = \mu + T_i + I_{(i)j} + E_k + TE_{ik} + EI_{(i)jk} + \varepsilon_{l(ijk)}$$

In the model μ is the mean, I represents the subjects, T represents the treatments (control, experimental), E constitutes the test (pre-test, mid-test, and post-test), S the score in the tests, and ε is the error. Tukey HSD was calculated for any statistically significant source of variability in the model.

4.2.6.2 Qualitative analysis

To answer the research question three regarding the influence of the visuo-haptic simulation in the conceptualization of electricity and magnetism concepts (refer to section 4.2), question six from the pre, post, and delayed post-test was examined. This question herein referred to as *Electrostatics Graphical Representation*, and had the following structure:

Electrostatics Graphical Representation: A **uniformly positively charged ring** is shown below. Draw arrows representing the force experienced by a **positive test charge placed** at points **A, B, C, D, and E**. The direction of each arrow should represent the direction of the force. The length of each arrow should represent the strength of the force at that point.

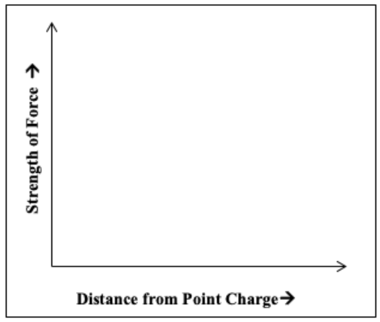


From the worksheet the following questions where selected for analysis:

- *Record table point*: Place the cursor at each point A, then B, then C. At each point, record the information in the table below:

Point	Distance of point from charge (use ruler to measure it)	Direction of the force arrow seen when you when you place your cursor at the point.,(Draw an arrow)	Strength of the force experienced by you when you place your cursor at the point (Read off value from screen)
A			
B			
C			

- *QP2*: Use the data above to draw a graph of Strength of Force vs. Distance from Point Charge.



- *QP3*: Based on the graph, if you double your distance from the point charge, how will the strength of the force change? i.e., will it double, halve, or something else?

A scoring rubric was developed for all the open response or graphical representation questions (See Appendix C). Assessments were scored independently. For this research work, two raters (R1 and R2) were used to rate subjects' answers. R1 scored 100% of the assessment while R2 rated 20%. The assessments scored by R2 were selected randomly for each experiment form the roster and R2 rated pre-test, post-test, and delayed post-test for the subjects selected. To determine if the level of agreement between the raters (R1 and R2) was superior to what would be likely by chance, the researches used Cohens κ (Gwet, 2002). The inter-rater reliability for each point and category were interpreted based on Cohens κ estimates as follows: less or equal to 0 indicated no agreement, from 0.01 to 0.20 none to slight agreement, from 0.21 to 0.4 denoted fair agreement, from 0.41 to 0.60 signaled a moderate agreement, from 0.61 to 0.80 implied substantial agreement, and from 0.81 to 1 is taken as an almost perfect agreement (McHugh, 2012). To determine if experimental and control treatments were comparable within each experiment the researchers conducted a One-Way ANOVA to the scores obtained in the pre-test. If experimented were comparable the researcher proceeded to conduct a nested factorial analysis to the scores of the pre-test, post-test, and delayed post-test within each experiment.

4.2.6.2.1. Level of agreement between the raters for *Electrostatics Graphical Representation*

The inter-rater reliability estimations are shown in Table 4.5. The Cohens κ indicated almost perfect agreement for AD, BD, CD, CL, DD, ED and substantial agreement for AL, BL, DL, EL. Thus, continuing with the remaining data analysis procedures was suitable.

Table 4.5. Cohens κ estimate, lower and upper confidence intervals (CI) at $\alpha = 0.05$.

Variable	Cohens Kappa	95% Lower CI	95% Upper CI
AD	0.9789	0.9377	1.0000
AL	0.7360	0.5903	0.8817
BD	0.8630	0.7464	0.9796
BL	0.7231	0.5558	0.8903
CD	1.0000	1.0000	1.0000
CL	1.0000	1.0000	1.0000
DD	0.9410	0.8602	1.0000
DL	0.7667	0.6035	0.9299
ED	1.0000	1.0000	1.0000
EL	0.7655	0.6205	0.9104

4.3 Results

This section contains quantitative and qualitative results obtained after the analysis of Electricity and Magnetism I, II, III, IV, and V data.

4.3.1 Experiments descriptive statistics

Tables 4.6, 4.7, 4.8, 4.9, and 4.10 detail the number of participants considered for the analysis (N), the minimum score obtained, the maximum score obtained, mean, and standard deviation (SD) for each test within every experiment. Only participants that completed all assessments were considered for analysis.

The second version of the assessments was used for the analysis, for pre / post / delayed post-test only the first four questions were considered, and all questions in the transfer / delayed transfer were used.

Table 4.6. Descriptive statistics for Electricity and Magnetism I pre-test, post-test, delayed post-test, transfer test, and delayed transfer test.

Test	Treatment	*N*	Min	Max	Mean	*SD*
Pre	H1	19	0	4	1.8421	1.2589
	V1	20	1	4	2.1500	1.0400
Post	H1	19	1	4	2.7368	0.9912
	V1	20	1	4	2.6500	1.0894
Delayed Post	H1	19	1	4	2.1579	0.8983
	V1	20	1	4	2.2000	0.9515
Transfer	H1	19	0	7	3.5789	1.8654
	V1	20	0	5	3	1.2566
Delayed Transfer	H1	19	2	6	3.5263	1.1239
	V1	20	0	5	2.500	1.3572

The descriptive statistics in Table 4.6 for *Electricity and Magnetism I* show an increment from pre-test to post-test for the mean for both treatments. The means in the delayed post-test, two weeks later, show a diminution when compared the post-test but not as low as in the pre-test. Additionally, the means of the delayed transfer test are lower than the ones obtained in the transfer test.

The analysis of *Electricity and magnetism II* showed the same pattern found in *Electricity and magnetism I*. The results presented in Table 4.7, show an increment on the means from pre-test to post-test and a decrease from post-test to delayed post-test. Again, a decrease in the means from the transfer test to delayed transfer test was observed.

Delayed post-test and transfer test were not collected in *Electricity and Magnetism III*. Table 4.8 shows that there was an increment in the scores means for both treatments. However, the increment for the control group (V3) group gas greater than for the experimental group (H3 $\rightarrow$ H3+V3).

Table 4.7. Descriptive statistics for Electricity and Magnetism II pre-test, post-test, delayed post-test, transfer test, and delayed transfer test.

Test	Treatment	*N*	Min	Max	Mean	*SD*
Pre	H2 → H2+V2	23	0	3	1.0435	0.9760
	V2	20	0	4	1.7500	1.4464
Post	H2 → H2+V2	23	1	4	2.2609	1.2511
	V2	20	0	4	2.3000	1.2183
Delayed Post	H2 → H2+V2	23	0	4	1.6522	1.1524
	V2	20	0	4	1.8000	1.0563
Transfer	H2 → H2+V2	23	1	7	4.0435	1.4610
	V2	20	1	7	3.8500	2.0333
Delayed Transfer	H2 → H2+V2	23	0	6	3.4348	1.5336
	V2	20	0	5	2.7500	1.4824

Table 4.8. Descriptive statistics for Electricity and Magnetism III pre-test, post-test, and delayed post-test.

Test	Treatment	*N*	Min	Max	Mean	*SD*
Pre	H3 → H3+V3	16	0	3	2.0625	0.8539
	V3	21	0	3	1.6190	1.0713
Post	H3 → H3+V3	16	0	4	2.3750	1.0878
	V3	21	0	4	2.1429	1.0142
Transfer	H3 → H3+V3	16	1	6	3.3125	1.2500
	V3	21	0	7	3.7143	1.7071

Experiment *Electricity and Magnetism IV* shows a different trend when compared with previous experiments. Both treatments means increased from pre-test to post-test data collection. The comparison of delayed post-test and post-test shows that the means increased for the control group (H4+V4) and decreased for the experimental group (V4).On the other hand, mean scores increased for the experimental group and decreased for the control group from the transfer test to the delayed transfer test (refer to Table 4.9).

Table 4.9. Descriptive statistics for Electricity and Magnetism IV pre-test, post-test, delayed post-test, transfer test, and delayed transfer test.

Test	Treatment	*N*	Min	Max	Mean	*SD*
Pre	H4+V4	25	0	4	1.7600	1.0520
	V4	32	0	3	1.5313	0.8793
Post	H4+V4	25	0	4	2.1200	1.2356
	V4	32	0	4	1.6250	1.0395
Delayed Post	H4+V4	25	0	4	1.8800	0.9713
	V4	32	0	4	1.6563	1.1807
Transfer	H4+V4	25	0	6	3.2000	1.4720
	V4	32	0	6	3.2813	1.5499
Delayed Transfer	H4+V4	25	0	6	3.3200	1.4059
	V4	32	1	5	2.5938	1.2407

Table 4.10. Descriptive statistics for Electricity and Magnetism V pre-test, post-test, delayed post-test.

Test	Treatment	*N*	Min	Max	Mean	*SD*
Pre	H5 → H5+V5	20	0	3	1.300	0.8645
	V5	11	0	3	1.5455	0.9342
Post	H5 → H5+V5	20	1	4	2.1500	0.9333
	V5	11	1	3	2.0909	0.8312
Transfer	H5 → H5+V5	20	1	6	3.9000	1.3727
	V5	11	0	4	2.7273	1.1031

Mean scores in *Electricity and Magnetism V* from pre-test to post-test show an increment (refer to Table 4.10). The increment for the experimental group (H5 → H5+V5) was greater than for the control group (V5).

4.3.2 Comparison of treatments within experiments

The null hypothesis stated that the mean of the pre-test scores of the two treatments was equal. The *Model* and the *Treatment F* tests for all the experiments are detailed in Table 4.11. For all experiments (Electricity and Magnetism I [$F(1, 37)$], II [$F(1, 41)$], III [$F(1, 35)$], IV [$F(1, 55)$], and V [$F(1, 29)$]) the overall *p-value* is greater than 0.05. Thus, we cannot reject the null hypothesis and conclude that the treatments had similar means at $\alpha = 0.05$ in the pre-test measures.

Table 4.11. One-Way ANOVA: Model *F* test and *F* test for Treatment of pre-test scores for Electricity and Magnetism I, II, III, IV, and V.

	F test			
	Model		Treatment	
Experiment	*F*	*p-value*	*F*	*p-value*
Electricity and Magnetism I	0.70	0.4094	0.70	0.4094
Electricity and Magnetism II	3.61	0.0646	3.61	0.0646
Electricity and Magnetism III	1.84	0.1831	1.84	0.1831
Electricity and Magnetism IV	0.80	0.3752	0.80	0.3752
Electricity and Magnetism V	0.54	0.4680	0.54	0.4680

(*) indicates that the *p-value* $\leq$ 0.05.

In Table 4.11 the *F* test for *Model* and *Treatment* was identical because *Treatment* there was only one variable considered for the analysis. Since, the pre-test scores within treatments were not statistically different from the post-test and delayed post-test scores for Treatment A and B, findings showed that the performance between groups was statistically equal thus the treatments could be contrasted. Also, the paired *t-test* between pre-test and post-test showed a significant statistical difference for the following haptic enhanced treatments: H1, H2 $\rightarrow$ H2+V2, and H5 $\rightarrow$ H5+V5. Additionally, the V3 treatment also showed a significant statistical difference. The paired *t-test* details are summarized in Table 4.12.

For H1 it can be observed an increment in the mean score from 1.8421 to 2.7368 and a decrease in the standard deviation from 1.2589 to 0.9912 (refer to Table 4.6). In the case of H2 $\rightarrow$ H2+V2 the mean score increased from 1.0435 in the pre-test to 2.2609 in the post-test and the standard deviation increased from 0.9760 to 1.2511 (refer to Table 4.7).

Table 4.12. The paired *t-test* between pre-test and post-test scores of Electricity and Magnetism I, II, III, IV, and V.

Experiment	Treatment	*t*	*p-value*
Electricity and Magnetism I	H1	-3.72	0.0016 *
	V1	-1.27	0.2198
Electricity and Magnetism II	H2 $\rightarrow$ H2+V2	-4.85	<0.0001 *
	V2	-1.53	0.1419
Electricity and Magnetism III	H3 $\rightarrow$ H3+V3	-1.05	0.3123
	V3	-2.14	0.0452 *
Electricity and Magnetism IV	H4+V4	-1.62	0.1191
	V4	-0.47	0.6384
Electricity and Magnetism V	H5 $\rightarrow$ H5+V5	-3.34	0.0034 *
	V5	-1.75	0.1113

(*) **indicates that the p-value $\leq$ 0.05.**

The V3 treatment increased the mean from 16190 to 2.1429 and decreased its standard deviation from 1.0713 to 1.0142 (refer to Table 4.8). Finally, the mean scores for the mean H5 $\rightarrow$ H5+V5 increased from 1.300 to 2.1500 and the standard deviation went from 0.8645 to 0.9333 (Table 4.10). Thus, we can conclude that post-test scores were significantly better than pre-test scores for H1, H2 $\rightarrow$ H2+V2, V3, and H5 $\rightarrow$ H5+V5. The results suggest that in the single modality experiment (Electricity and Magnetism I) and in two of the sequenced modality experiments (Electricity and Magnetism II and V) students in the experimental treatment (haptic enhanced) benefited by acquiring content knowledge.

When compared mean gain scores between experiments, the two-sample t-test showed that we cannot reject the null hypothesis. Thus, post-test scores for the two treatments were not significantly different within treatments A and B of Electricity and Magnetism I, II, III, IV, and V (refer to Table 4.13).

Even though, the mean post-test scores were significantly better than pre-test scores for H1, H2 $\rightarrow$ H2+V2, V3, and H5 $\rightarrow$ H5+V5 (refer to Table 4.12) the paired t-test in Table 4.13 there is no statistical evidence to conclude that the experimental treatment performed better than the control treatment group.

Table 4.13. Two Sample *t-test* between control and experimental scores of Electricity and Magnetism I, II, III, IV, and V.

Experiment	*t*	*p-value*
Electricity and Magnetism I	0.26	0.7963
Electricity and Magnetism II	-0.10	0.9180
Electricity and Magnetism III	0.67	0.5082
Electricity and Magnetism IV	1.64	0.1063
Electricity and Magnetism V	0.18	0.8623

(*) indicates that the p-value $\leq$ 0.05.

The nested factorial analysis was only applied to Electricity and Magnetism I (single modality), II (sequenced modality), and IV (simultaneous modality) because only these experiments collected delayed post-test. For Electricity and Magnetism I and II the analysis indicated that there is a significant difference between tests (pre-test, post-test, and delayed post-test) for both treatments (A and B). However, participants in both treatments demonstrated similar performance (refer to Tables 4.14 and 4.16). The analysis for Electricity and Magnetism IV showed that there is no significant difference between treatments nor between tests. Please refer to Table 4.18 for details.

Table 4.14. Nested Factorial Analysis for Electricity and Magnetism I.

Source	*F* Ratio	*p-value*
Treatment	0.1374	0.7130
Test	6.2352	0.0031*
Test x Treatment	0.4830	0.6188

(*) indicates that the *p-value* $\leq$ 0.05.

The analysis of Tukey HSD, in Table 4.15, for *Electricity and Magnetism I* shows that pre-test and delayed pot-test least square means are not scientifically different and can be grouped together. On the other hand, the post-test least square mean is statistically different. In other words, participants' scores decreased to the pre-test level after two weeks.

Table 4.17 shows that delayed post-test and pre-test can be grouped, but pre-test least square mean is statistically different from the other two. Thus, we can conclude that for both treatments scores increased, and two weeks later the scores decreased again to the level of the pre-test scores for *Electricity and Magnetism II*.

Table 4.15. Electricity and Magnetism I least squares means differences, Tukey HSD.

Level			LSMean
Post-test	A		2.6934
Delayed post-test		B	2.1789
Pre-test		B	1.9960

Levels not connected by same letter are significantly different.

Table 4.16. Nested Factorial Analysis for Electricity and Magnetism II.

Source	*F* Ratio	*p-value*
Treatment	0.1769	0.2843
Test	9.3824	0.0002*
Test x Treatment	1.5080	0.2274

(*) indicates that the *p-value* $\leq$ 0.05.

Table 4.17. Electricity and Magnetism II least squares means differences, Tukey HSD.

Level			LSMean
Post-test	A		2.2804
Delayed post-test		B	1.7260
Pre-test		B	1.3967

Levels not connected by same letter are significantly different.

Table 4.18. Nested Factorial Analysis for Electricity and Magnetism IV.

Source	*F* Ratio	*p-value*
Treatment	1.8987	0.1736
Test	1.3920	0.2529
Test x Treatment	0.3318	0.7184

(*) indicates that the *p-value* $\leq$ 0.05.

With the results obtained in this section, we can conclude that there is not enough evidence to reject H_{01}. In other words, the addition of tactile stimulus to an electricity and magnetism computer-based simulation had no effect on conceptual knowledge about the subject.

4.3.3 Comparison of treatments between treatments

There was not a significant statistical difference in the pre-test scores at the $p<0.05$ level for the ten (10) conditions [$F(9, 162) = 1.78$, $p = 0.0763$]. Thus, we can contrast experiments between each other. Figure 4.8 shows the distribution of means for all the treatments. Since we established that the scores on the pre-tests for all the treatments were

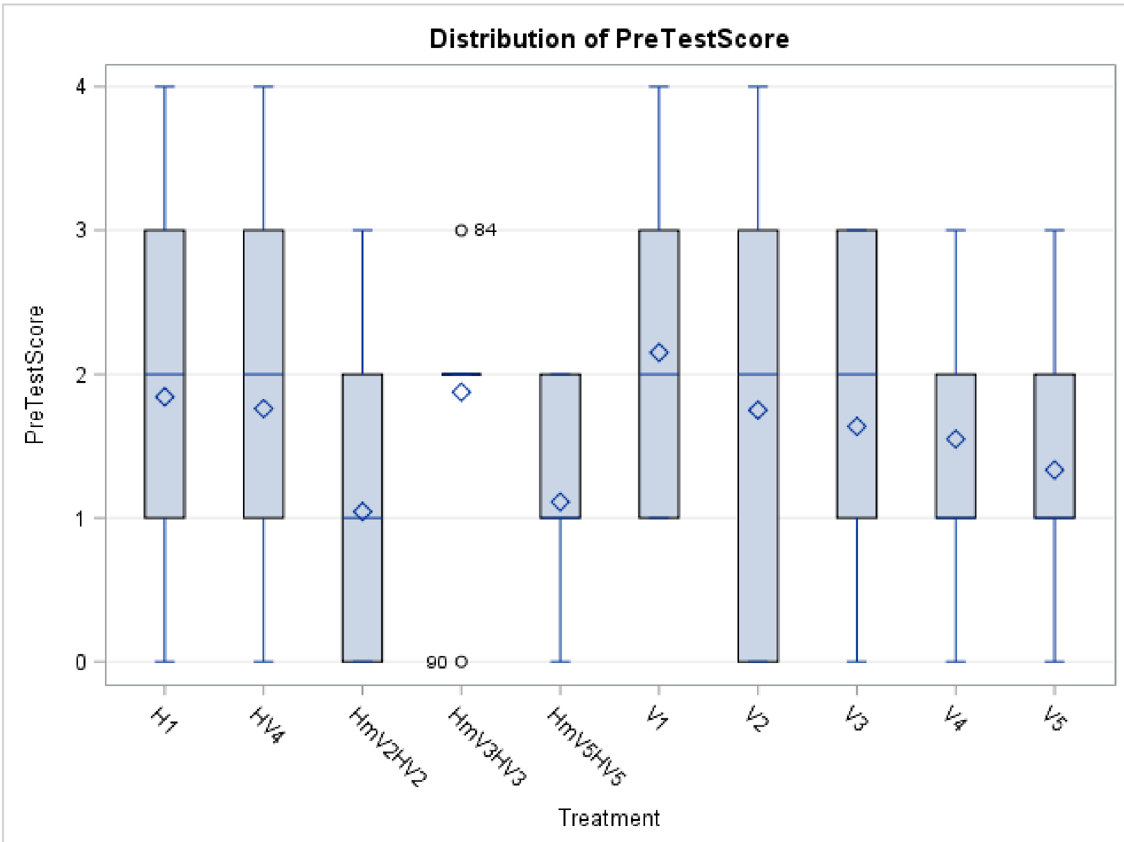


Figure 4.8. Distribution of pre-test scores for experiments I, II, III, IV, and V

not statistically different. Thus, experiments with the same treatments were merged including treatments $V1+V2+V3+V4+V5$ were grouped and renamed as V, and H2 $\rightarrow$ H2+V2, H3 $\rightarrow$ H3+V3, and H5 $\rightarrow$ H5+V5 were now labeled as H $\rightarrow$ H+V. There was not a significant statistical difference in the post-test scores at the $p<0.05$ level for the four (4) conditions, including the two single modalities, the sequenced, and the simultaneous [F(3,

203) = 1.93, p = 0.1262]. In other words, all treatments yielded similar post-test scores. We can, therefore, conclude that there is not enough evidence to reject H_{02}. The modality (single, sequenced, simultaneous) used in the electricity and magnetism computer-based simulation did not affect students' development of conceptual learning in the subject.

4.3.4 Perceived accuracy of responses and helpfulness of haptic device

One of the questions in the worksheet asked the following: How confident do you feel about the accuracy of the responses have provided for questions on this worksheet? This question provided a 5-point Likert scale (Highly Confident, Confident, Neutral, Not Confident, and Highly Not Confident), so students could provide a score to this question. Results are summarized in Table 4.19, for Electricity and Magnetism I and II most of the participants in treatment A and B felt neutral about their confidence in the answers provided. However, in Electricity and Magnetism V most of the students in H5 →H5+V5 did not feel confident. In V5 participants felt neutral.

Table 4.19. Percentages of participants for question: How confident do you feel about the accuracy of the responses have provided for questions on this worksheet?

Exp.	Tmt	Highly Confident [%]	Confident	Neutral [%]	Not Confident [%]	Highly Not Confident [%]	No Response [%]
II	H2 →H2+V2	7.14	14.29	50	10.71	10.71	7.14
	V2	7.69	19.23	42.31	26.92	3.85	0
III	H3 →H3+V3	5.88	29.41	47.06	11.76	5.88	0
	V3	0	33.33	33.33	28.57	4.76	0
V	H5 →H5+V5	5.00	35.00	15.00	45.00	0	0
	V5	0	0	45.45	18.18	36.36	0

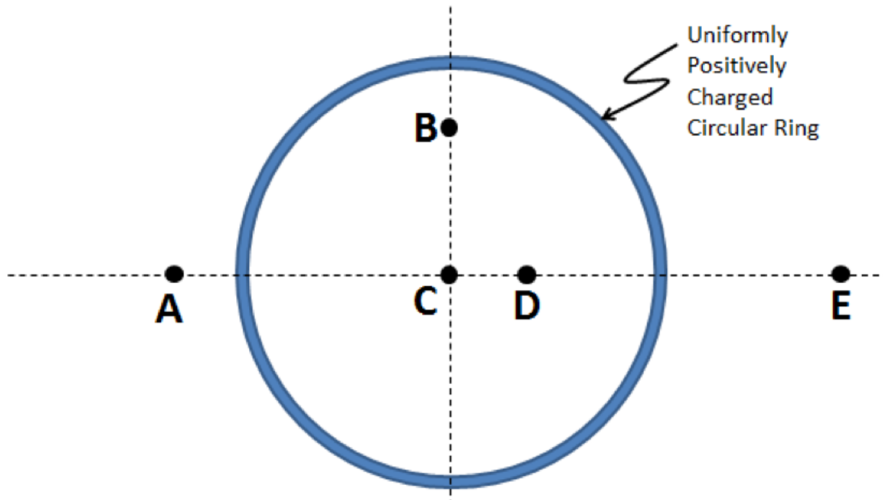
Students were also asked to rate the following statement: I felt that the simulations helped me to respond the questions on this worksheet. This question also provided a 5-point Likert scale (Strongly Agree, Agree, Neutral, Disagree, and Strongly Disagree). Participants in the sequential modality treatments in Electricity and Magnetism I, II, and III perceived that the simulations helped them to answer the worksheet questions. On the other hand, the visual treatments were divided between agreeing and neutral perceptions of helpfulness. Please refer to Table 4.20.

Table 4.20. Percentages of participants for question: I felt that the simulations helped me to respond the questions on this worksheet.

Exp	Tmt	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	No Response
II	H2 →H2+V2	14.29	42.86	17.86	17.86	0	7.14
	V2	15.38	34.62	34.62	11.54	0	3.85
III	H3 →H3+V3	17.65	47.06	17.65	11.76	5.88	0
	V3	9.52	42.86	38.10	9.52	0	0
V	H5 →H5+V5	10.00	60.00	25.00	5.00	0	0
	V5	9.09	36.36	18.18	18.18	18.18	0

4.3.5 Qualitative analysis of *Electrostatics Graphical Representation*

Only students that filled out the three assessments were considered for the data analysis. Pre-test, post-test, and delayed post-test contained the same seven multiple-choice questions and one open-ended question. The following open-ended question was analyzed qualitatively for pre-test, post-test, and delayed post-test for *Electricity and Magnetism I*, *II*, and *IV*.: A **uniformly positively charged ring** is shown below. Draw arrows representing the force experienced by a **positive test charge placed** at points **A, B, C, D, and E**. The direction of each arrow should represent the direction of the force. The length of each arrow should represent the strength of the force at that point.



4.3.5.1 Comparison of treatments within experiments

Students' responses to the question were scored with a rubric. The scores were then analyzed quantitatively. The results of the One-Way ANOVA for each experiment are shown in Table 4.21. The p-values obtained show that there is not a significant difference between the pre-test scores of the experimental treatment and the control treatment within each experiment round. Thus, changes in the post-test and delayed-test scores can be examined within each experiment. Table 4.22 summarizes descriptive statistics for all the treatments within each experiment.

Table 4.21. Equality of variances for pre-test scores of *Electrostatics Graphical Representation*

Experiment	Equality of Variances
Electricity and Magnetism I	F=3.5120, p=0.0686
Electricity and Magnetism II	F=0.1571, p=0.6939
Electricity and Magnetism IV	F=0.7634, p=0.3870

(*) indicates that the p-value $\leq$ 0.05.

The results of the nested factorial analysis are shown in Table 4.23. For *Electricity and Magnetism I* the sources *Treatment* and *Test* are statistically different. However, the interaction *Test*Treatment* did not control for the subject to subject variation. In other words, V1 (treatment B) performed better than H1 (Treatment A) in all the assessments, but the difference increased on a homogeneous rate for both (Figure 4.9(a)). The analysis of

Electricity and Magnetism II showed a statistically significant difference for *Test* and *Test*Treatment*. Thus, the interaction *Test*Treatment* showed that H2 $\rightarrow$H2+V2 scores increased for the post-test and were maintained until the delayed data collection (2 weeks later) and V2 increased its score in the post-test data collection. However, after two weeks, this group reverted to the state they were before interacting with the simulation (Figure 4.9(b)). Finally, for *Electricity and Magnetism IV Treatment* and *Test* Treatment* did not control for subject to subject variation. Thus, there was a significant difference between the scores on the tests. However, the treatment did not play a role in the variation of the score (Figure 4.9(c)).

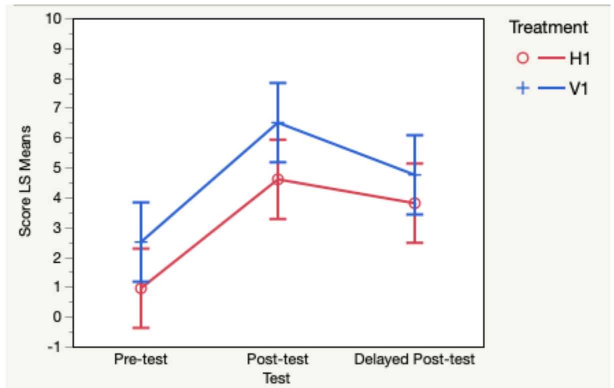
Table 4.23. Electrostatics Graphical Representation nested factorials results.

		EM I		EM II		EM IV	
Source	DF	F Ratio	p-value	F Ratio	p-value	F Ratio	p-value
Treatment	1	4.9833	0.0316*	2.9320	0.0944	0.0011	0.9741
Test	2	21.7322	$<$0.0001*	8.8482	0.0003*	6.9635	0.0016*
Test*Treatment	2	0.7195	0.3306	3.2334	0.0445*	0.9263	0.3998

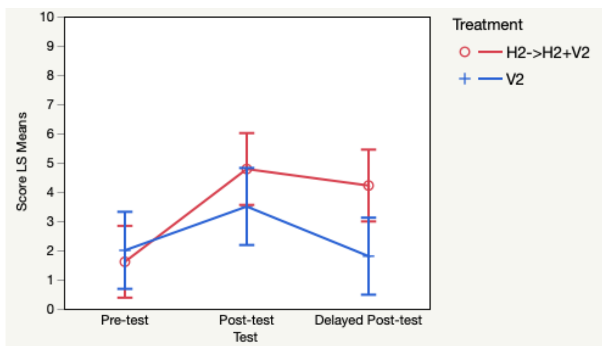
(*) indicates that the *p-value* $\leq$ 0.05.

4.3.6 Qualitative analysis of worksheet

Students' responses on the worksheet were also analyzed. To determine which questions of the worksheet should be analyzed the researcher first determined change frequency. Change frequency was determined by counting which questions were altered after enabling visual feedback. Tables 4.24 and 4.25 show change frequency for all questions in the worksheet.



(a)



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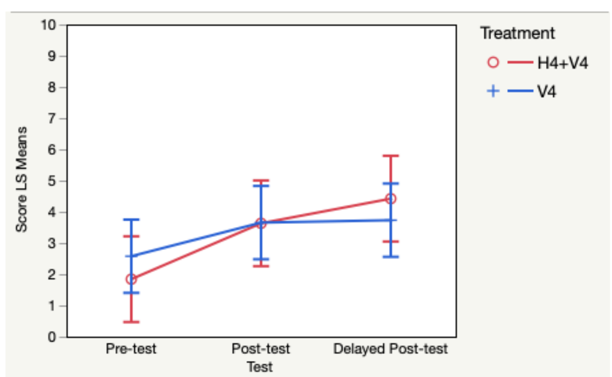


(c)

Figure 4.9. Treatments vs. assessments LS Means Plot of (a) EMI, (b) EII, and (c) EIV.

Experimental: ○ ——, control: + ——.

Question QP3 (Based on the graph, if you double your distance from the point charge, how will the strength of the force change? i.e. will it double, halve, or something else?), QL3 (Compare the graph you sketched for the positive point charge with the positive infinite line charge. - What are the similarities between the two graphs? Be as specific as you can. - What are the differences between the two graphs? Be as specific as you can). Were influenced the most by visual stimuli.

The experiments analyzed were sequenced (*Electricity and Magnetism II, III,* and *V*), participants in these experimental groups were asked to fill out the worksheet first with one color pen and when the rich visual feedback was activated participants changed or completed the worksheets with a red pen if necessary. Analysis of QP2 (Use the data above to draw a graph of Strength of Force vs. Distance from Infinite Line Charge). In experiment II 96.15% (25) of participants in V1 responded correctly the question, 3.85% (1) participants answered incorrectly (refer to Figure 4.10).

Figure 4.11 presents the two types of correct figures found in the responses. In Appendix C in Figure C.2. In Figure 4.11(a) it seems that participants interpret the relationship as discrete as if only the three points existed. In Figure 4.11(b) participants present a continuous representation of the interaction of strength of force and distance from the point charge. On the other hand, 3.57% (1) of H2 responded correctly and 96.43% (27) incorrect (Figure 4.12), after adding visual cues (H2+V2) 28.57% (8) responded correctly (Figure 4.13) and 71.43% (20) incorrect, however, of the incorrect 65%(13) were inversely proportional (Figure 4.12(d)) and 35% (7) directly proportional (Figure 4.12(c)). None of the participants in the visual-only treatment drew a directly proportional relationship.

The experiment III responses showed a 38.10% (8) of correct responses and 61.90% (13) incorrect for V3, from which 15.38% (2) drew a directly proportional relationship (refer to Figure 4.10). In the experimental treatment first stage (H3) 100% (17) responded incorrectly, in the second stage (H3+V3) 11.76% (2) were correct and 88.24% (15) incorrect, from which 66. 67% (10) drew an inversely proportional relationship.

In experiment V 45.45% (5) participants of the control group (V5) answered correctly and 54.55% (6) incorrectly (refer to Figure 4.10), from which 50% (3) drew a directly proportional relationship and 16.67% (1) a parable. In the first stage (H5) and second stage (H5+V5) of Treatment A 15% (3) answered correctly and 85% (17) incorrectly, from which 58.82% (10) drew inversely proportional relationship.

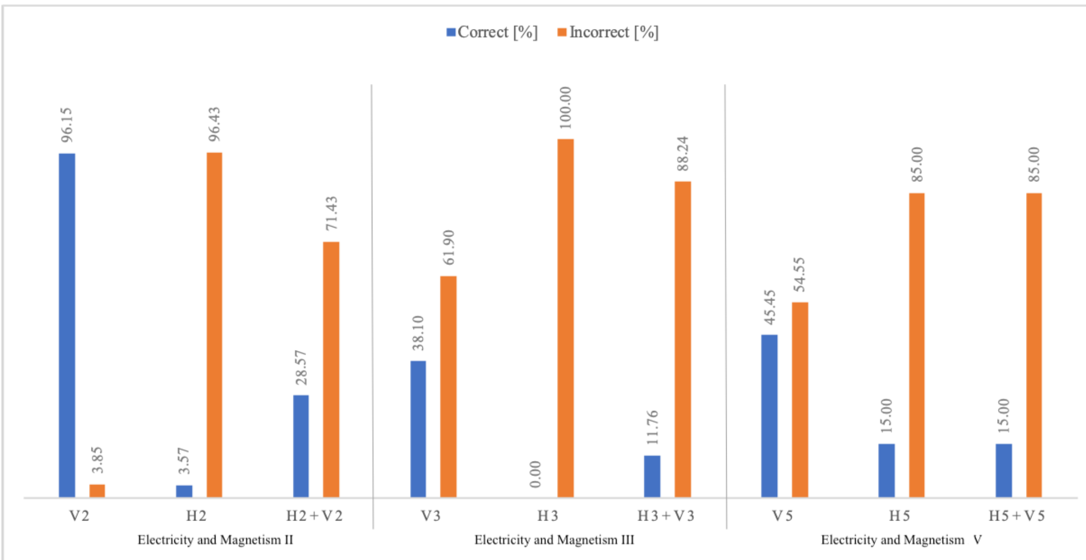
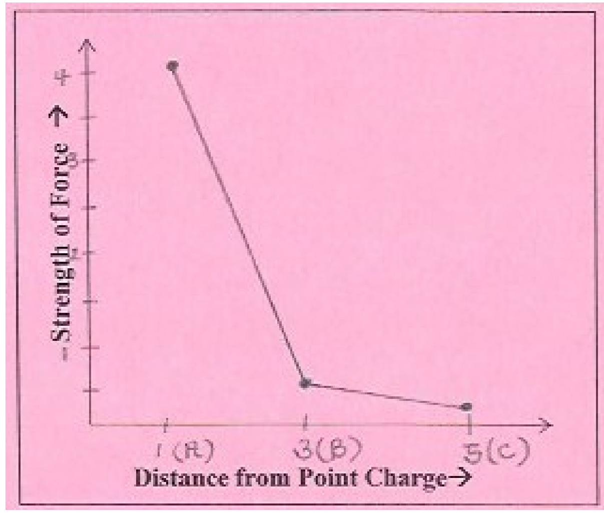
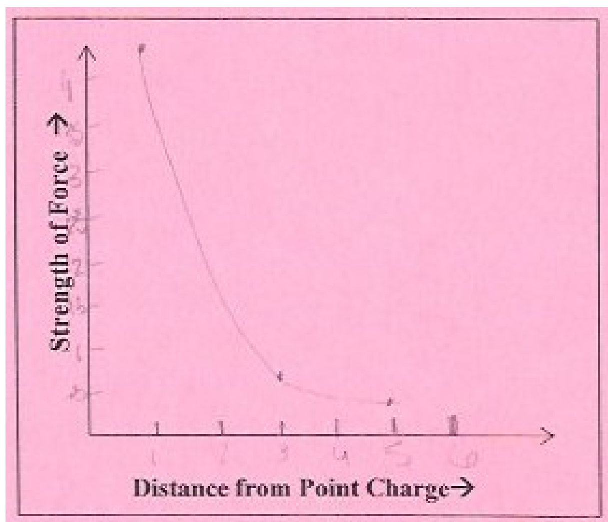


Figure 4.10. Percentage of correct and incorrect responses for QP2 in experiment II, III, and V.

Participants in the experimental treatments used the additional visual feedback in QP2 to change or reinforce their previous answers.



(a)

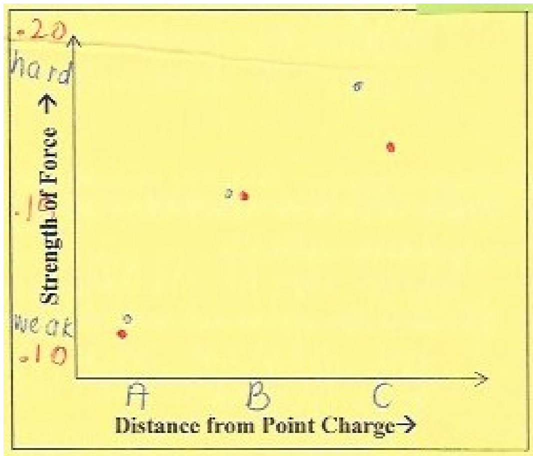


(b)

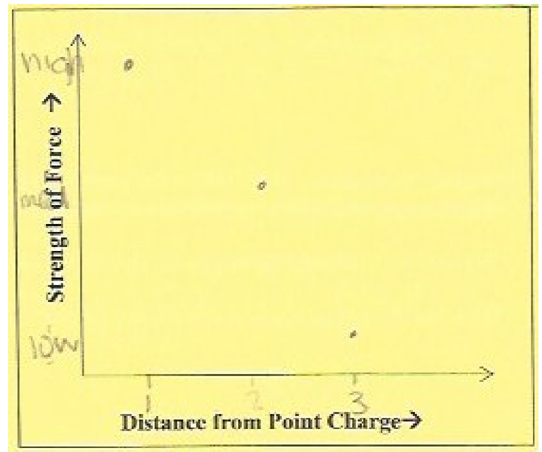
Figure 4.11. Correct drawings identified in participant responses for question QP2 (a) joint points and (b) exponential relationship.

4.4 Summary of Findings

- There is a significant difference between the mean scores of pre-test and post-test of *Electricity and Magnetism I, II, III, and V*; however, both treatments within each experiment performed similarly.



(a)



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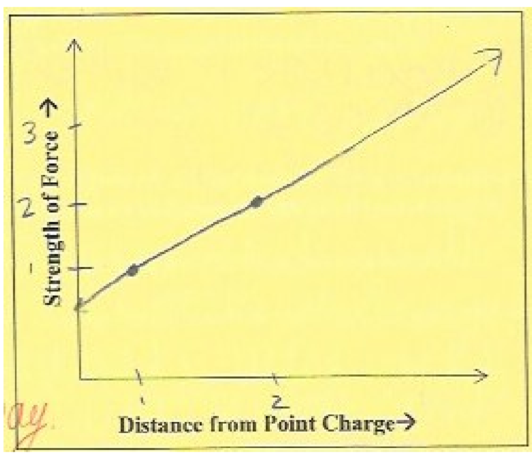

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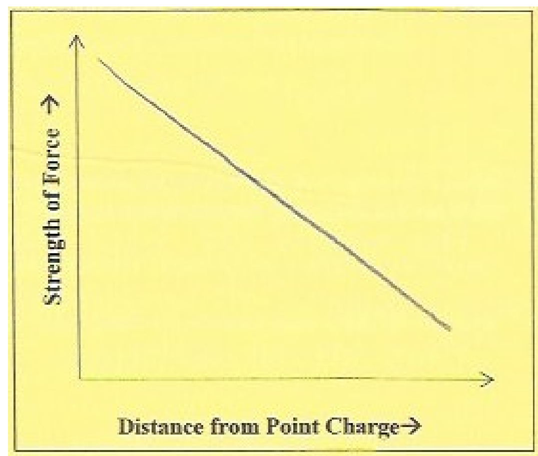


(d)

Figure 4.12. Incorrect drawings identified in participant responses for question QP2 (a) and (c) directly proportional, (b) and (d) inversely proportional.

- Mean post-test scores of treatment A (haptically enhanced) and B (rich visual cues) were not statistically different for any of the *Electricity and Magnetism* experiments.
- Post-test scores in *Electricity and Magnetism I* and *II* increased after treatment application, however, after two weeks mean scores decreased to the level of the pre-scores.
- We can not reject H_{01} and H_{02} with a significance level (α) of 0.05.

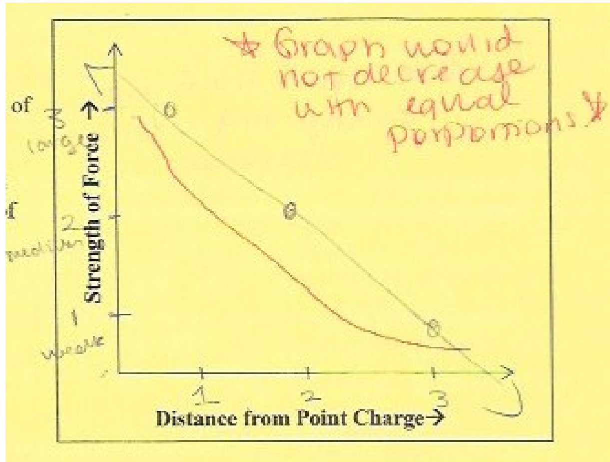


Figure 4.13. Correct answer for QP2 when visual stimuli was enabled

- The analysis of *Electrostatics Graphical Representation* showed that *Electricity and Magnetism I* treatments yield statistically equal scores. *Electricity and Magnetism II* increased the score on the post data collection; however, only H→H+V maintained the score in the delayed data collection. Suggesting that the sequential modality allowed for retrieval even 2 weeks later. Simultaneous modality (H4+V4) showed a slight increase in scores when compared with V4. However, both treatments were comparable. We can conclude that the sequential modality benefited the conceptual understanding of electrostatics when are asked to draw the force system.

Table 4.22. Electrostatics Graphical Representation pre-test, post-test, and delayed post-test number of participants (N), minimum score (Min), maximum score (Max), mean (μ), standard deviation (SD).

			Pre-test				Post-test				Delayed post-test			
Exp.	Tmt.	N	Min	Max	μ	SD	Min	Max	μ	SD	Min	Max	μ	SD
I	H1	20	0	8	0.95	2.01	0	10	4.60	3.55	0	10	3.80	3.25
	V1	20	0	10	2.50	3.10	2	10	6.50	2.56	0	10	4.75	3.23
II	H2 →H2+V2	23	0	10	1.61	3.17	0	10	4.78	3.34	0	10	4.22	3.19
	V2	20	0	10	2.00	3.29	0	8	3.50	2.33	0	6	1.80	2.14
IV	H4+V4	19	0	8	1.84	2.52	0	10	3.63	2.93	0	10	4.42	3.45
	V4	27	0	10	2.56	2.86	0	10	3.59	2.94	0	10	3.81	3.37

Table 4.24. Change frequency for experiments II, III, and V

	Experiment			
Question	II	III	V	Total
QP1	1	4	6	11
QP2	11	8	6	25
QP3	17	11	9	37
QP4	1	5	3	9
QL1	4	5	2	11
QL2	9	8	5	22
QL3	15	10	9	34
QL4	11	8	7	26
QL5	1	4	6	11
QRA1	6	9	11	26
QRA2	4	10	7	21
QRB1	4	6	6	16
QRB2	3	7	4	14
QR3	3	6	6	15
QR4	4	6	5	15

Table 4.25. Change frequency for record tables in experiments II, III, and V.

		Attribute		
Experiment	Record Table	Unit	Direction	Strength
II	Point	0	1	13
	Lane	0	4	11
III	Point	3	6	13
	Lane	3	6	10
V	Point	1	4	11
	Lane	2	6	12
Total	Point	4	11	37
	Lane	5	16	33

CHAPTER 5. EXPERIMENTS AND RESULTS BUOYANCY

5.1 Learning Design

This section details the learning objectives and activities used to teach about buoyancy using visuo-haptic simulations and hands-on learning activities. Additionally, this section covers visuo-haptic simulations affordances and embodied design applied to the learning environment design.

This study aims to determine the impact of using combinations of physical and virtual manipulatives in participants' conceptual knowledge, misconceptions, and language about buoyancy. The combination of physical and virtual manipulatives could allow combining their affordances, however, it is necessary to determine which combination better facilitates conceptual understanding of buoyancy.

5.1.1 The visuo-haptic simulation and hands-on interaction

To carry out this experiment two learning environments were set up: Visuo-haptic simulation and physical hands-on. The visuo-haptic simulation allowed students to try variations of: (a) Liquid density (0.1-1[$^{g}/_{cm^3}$]), (b) Object density (0.1-1[$^{g}/_{cm^3}$]), and (c) Object size (0.1-1). Additionally, the simulation provided haptic feedback correlated with the visual output (refer to Figure 5.1). On the other hand, the physical hands-on activity incorporated the utilization of two objects and two different fluids. Participants were asked to submerge each object in the two fluids (refer to Figure 5.2). Participants experienced the forces through a piece of string that was attached to the object and held to submerge the object.

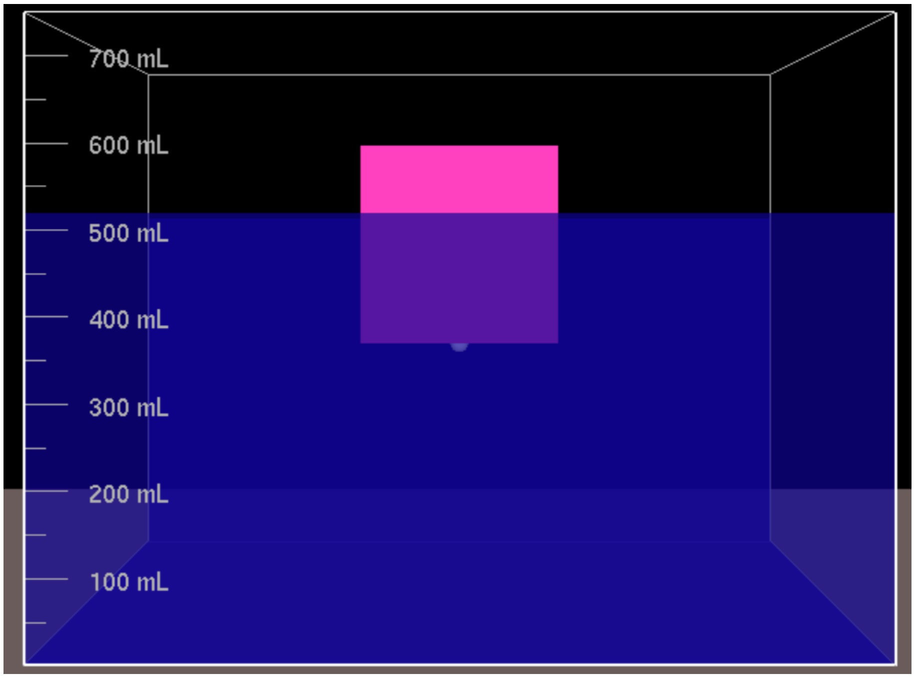


Figure 5.1. Buoyancy experiment 1: Liquid density = $0,1[^{g}/_{cm^3}]$, object density = $0,1[^{g}/_{cm^3}]$ and object size =0.5.

5.1.2 The haptic device

The haptic force feedback is simulated using a Novin Falcon game controller with a standard interchangeable grip, which can provide 3 DoFHapticsHouse.com (2017). Technical details are specified in section 4.1.2.

Figure 5.3 shows a participant interacting with the haptic device. Participants used their dominant hand for haptic exploration.

5.1.3 The worksheet

The worksheet for this series of experiments aimed to help students to understand the relationship between fluid and object densities in the concept of buoyancy. The worksheets were designed to guide participants during their interactions with the haptic device or the physical manipulatives.

Figure 5.2. Buoyancy physical hands-on experiment 4.

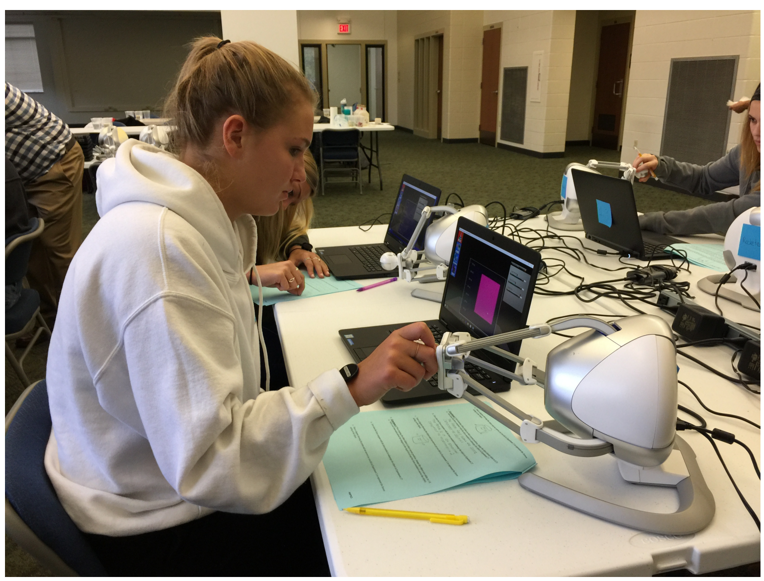


Figure 5.3. Novin Falco haptic device for buoyancy visuohaptic simulation

5.1.3.1 Embodied design principles

This research used embodied cognition as the theoretical framework to guide the hands-on and visuo-haptic experiments and create materials. Embodied cognition theory considers that the construction of knowledge is linked to bodily interactions (Neri et al., 2015). This theory posits that touch has a central role in humans' spatial perception. It also enables learners to feel, classify, and put in context the input compiled with assistance of sight, hearing, smell, and taste (Hatzfeld & Kern, 2014a).

Symbolic representations on the activities were kept to a minimum. The visuo-haptic representations simulation used graphical representations except for the menu. On the other hand, physical manipulatives were used by the hands-on treatment. On the physical hands-on experience, participants had a complete sensory experience, while on the visuo-haptic simulation only vision and touch were enabled. The task in the worksheets started with equal fluid and object densities, then the liquid density is changed, finally, the object density is changed. Worksheets also asked participants to provide explanations of what they were observing.

5.2 Research Design

This section details research design guidelines for the *Buoyancy* experiments.

5.2.1 Research questions and hypotheses

The following research questions were used to guide the work:

- Does a visuo-haptic simulation influence development of conceptual learning of buoyancy when compared to a laboratory hands-on experience?
  H_{o3}: A visuo-haptic simulation has no effect on their final conceptual knowledge about buoyancy.
  H_{a3}:A visuo-haptic simulation will affect their final conceptual knowledge about Buoyancy.

- How does the interaction with a visuo-haptic simulation influence scientific conceptualization of buoyancy?

5.2.2 Treatment conditions

Two learning activities were used to explore this linear abstract concept: (i) visuo-haptic simulation, and (ii) physical hands-on experiment. Experimental conditions for each cohort were labeled as Buoyancy accompanied by a Roman numeral. The experimental design implemented in *Buoyancy I* was a crossover design, in which the visuo-haptic simulation was followed by the physical hands-on laboratory for one group and vise versa for the other. For *Buoyancy II* design was experimental, in which the physical hands-on laboratory was used as the control group and the visuo-haptic simulation as the experimental group. Table 5.1 shows a summary of how the treatments were implemented.

Table 5.1. Buoyancy I and II and applied treatments for each one

Experiment	Academic Period	Treatment A	Treatment B
Buoyancy I	Spring 2017	Physical hands-on experiment followed by visuo-haptic simulation	Visuo-haptic simulation followed by physical hands-on experiment
Buoyancy II	Spring 2018	Visuo-haptic Simulation	Physical hands-on experiment

5.2.3 Context and Participants

A total of 121 students participated in the buoyancy experiment. Please refer to Table 5.2 for details. Participants in *Buoyancy I* were 51 undergraduate students. A 74.51%

Table 5.2. Buoyancy experiments participants

Experiment	Academic Period	Treatment A	Treatment B	Total
Buoyancy I	Spring 2017	26	25	51
Buoyancy II	Spring 2018	38	32	70

of the students were working on a degree in Elementary Education, 21.57% on an education related major, and 3.92% on a major not related to education. Participants' academic year distribution was 21.57% freshman, 39.22% sophomore, 37.25% junior, and 1.96% senior. Only 43.14% took a physics course in high school and only 1.96% has taken a physics class at the undergraduate level.

5.2.4 Procedures

- Buoyancy I: Participants fist completed the pre-test, then depending on their randomized assignment of treatment the participants used the physical hands-on worksheet or the visuo-haptic simulation worksheet first, when finished participants completed the mid-test and switched to the other worksheet. After completing both hands-on and visuo-haptic tasks, participants filled out a post-test and a haptics usability survey (Figure 5.4).

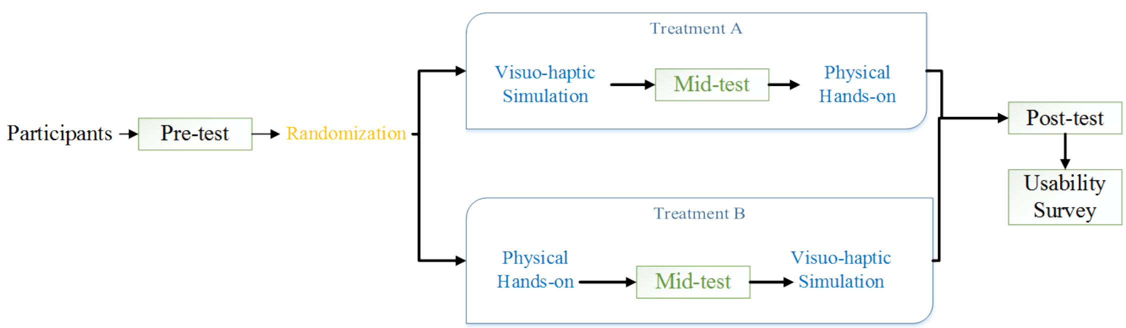


Figure 5.4. Procedures of experiment Buoyancy I

- Buoyancy II: Participants filled out first the pre-test, then completed either the visuo-haptic or the hands-on worksheet' tasks. Then all participants completed the post-test, but only the participants in the visuo-haptic group completed the haptics usability survey (Figure 5.5).

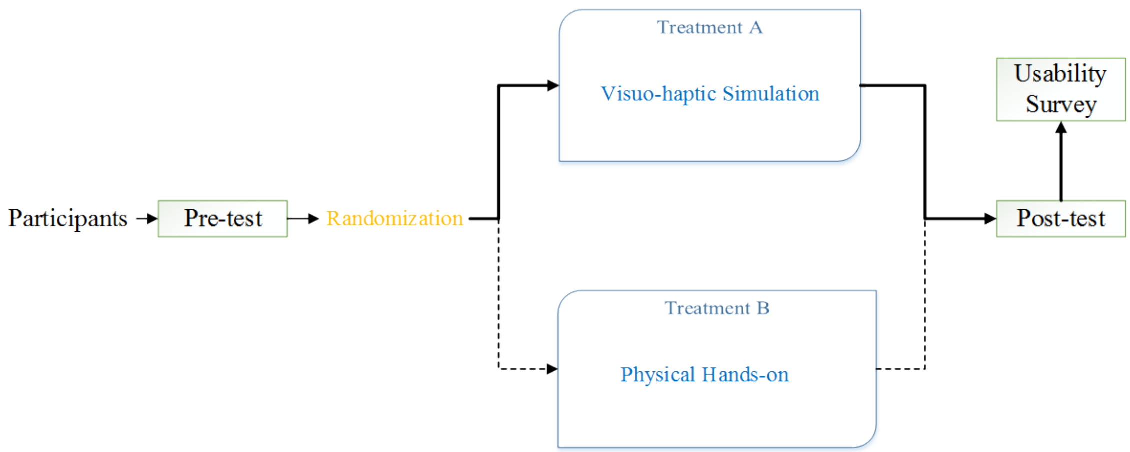


Figure 5.5. Procedures of experiment Buoyancy II

5.2.5 Data collection method

The data was collected during the laboratory hours of two sections of PHYS 215: Physics for Elementary Education. Each section was divided in half and randomly assigned a treatment. For experiments *Buoyancy I* and *II* a test for assessing concept knowledge was created and used to determine the initial state of knowledge and proficiency after the treatments were applied. Additionally, laboratory guidelines, called worksheets, were created to lead the participants in their **visuo-haptic simulation** and **physical hands-on experiment** learning activities. Finally, an assessment to determine the usability of haptic technology was implemented. Responses from tests were transcribed to a digital format and then qualitatively analyzed by the researchers.

- Pre-test, mid-test, post-test: The content knowledge assessment incorporated seven open-ended and six multiple-choice questions and seven open-ended questions. Additionally, this assessment used the same demographic questions used on the Electricity and Magnetism experiments (refer to section 4.2.5). The full assessment can be found in Annex B, the following are examples of the questions used:

1. The buoyant force on an object is dependent on:
   (a) the object's density
   (b) the mass of the object
   (c) the submerged volume of the object
   (d) the shape of the object
   (*StudyLib*, 2016)
2. An object can float provided its is than the of the fluid
   (a) mass . . .less . . . mass
   (b) density . . . less . . . density
   (c) mass . . .greater . . .density
   (d) density . . . less . . . mass
   (*StudyLib*, 2016)
3. Oil has a smaller density than water. Therefore, an object that will float in oil will:
   (a) float in water, with more of the object submerged
   (b) float in water, with the same amount of the object submerged
   (c) float in water, with less of the object submerged
   (d) not float in water
   (*StudyLib*, 2016)

- Visuo-haptic simulation and physical hands-on worksheets: The worksheets were divided into two sections. The first section was designed to guide students through different scenarios. The second section presented questions for testing conceptual knowledge. Activities are detailed on Annex B, the following is a summary of the content for each worksheet:
  - In the visuo-haptic simulation participant worked thought four experiments:

1. In this scenario, the liquid and the object density are equal to $0,1[{}^{g}/_{cm^3}]$. Participants were asked to write down their observations about water level and force needed to submerge the object and to draw the perceived forces acting on the object.
2. In this experiment, students incremented the fluid's density to $0,5[{}^{g}/_{cm^3}]$. Additional to the observations of water level and force, students recorded the difference in force needed in comparison with Experiment 1.
3. In this experiment participants incremented the object's density to $0,5[{}^{g}/_{cm^3}]$. Again, participants were asked to keep detailed records of their observations.
4. In the final experiment, participants needed to increment the object's size to 1 and record their observations.

– The worksheet for the physical hands-on activity provided four scenarios of the activity. Students were asked to keep detailed records of their observations related to the fluid level and force required to submerge and to surface the object, and to draw a diagram about the forces involved in the experiment:

1. The first experiment used water as the fluid and the object was a small potato.
2. The second experiment used corn syrup as the fluid and the object was a small potato.
3. The third experiment used corn syrup as the fluid and the object was a small rock.
4. The fourth experiment used corn syrup as the fluid and the object was a large rock.

- The haptic usability survey: This assessment was designed to survey the perceptions of participants towards haptic technology. The survey is the same used for the Electricity and Magnetism experiments which are detailed in section 4.2.5.

5.2.6 Data analysis method

A quantitative analysis was used for the exploration of treatment effect. On the other hand, a qualitative analysis was used to explore misconceptions and linguistic changes.

5.2.6.1 Quantitative analysis

For the quantitative analysis of Buoyancy I the researcher used a two-stage procedure. First, a one-way ANOVA to determine if the treatments are comparable. If the samples were comparable, a Nested Factorial analysis was conducted to compare the effect of each treatment on the pre-test, mid-test, and post-test scores. The nested factorial model used for the analysis:

$$S_{ijkl} = \mu + T_i + I_{(i)j} + E_k + TE_{ik} + EI_{(i)jk} + \varepsilon_{l(ijk)}$$

In the model μ is the mean, I represents the subjects, T represents the treatments (control, experimental), E constitutes the test(pre-test, mid-test, and post-test), S the score in the tests, and ε is the error.

For the quantitative analysis of Buoyancy II the researcher first conducted a one-way ANOVA using the treatments' pre-test scores; this statistical test allowed the researcher to determine if the treatments were comparable. Second, if the treatments were comparable, the researcher will proceed to conduct a paired t-test to contrast scores within treatment data collections to determine if there is a significant difference between data collections of the same treatment. Finally, the researcher tested if there is a difference between the treatments.

5.2.6.2 Qualitative analysis

Qualitative data were transformed into quantitative data to perform statistical analysis. Scoring rubrics were applied to open-ended questions and drawings of interest. Once students' responses were scored using the rubrics, descriptive statistics (mean, mode, and standard deviation) can be calculated for each treatment. The open-ended question of interest was: “Please provide an explanation of why you think some objects float in a liquid, while others sink. You may use diagrams if you wish. Please try to be as scientific as you can in your explanation.” Responses from both tests were transcribed to a digital format and then qualitatively analyzed by the researcher.

The analysis was divided into two main parts: (*i*) determination of misconceptions, and (*ii*) examination of language changes. For analysis purposes the sampled population was divided into six groups:

- Treatment A-Pre: Participants that started with hands-on experience, responses of pre-test.
- Treatment B-Pre: Participants that started with haptic experience, responses of pretest.
- Treatment A-Mid: Participants that started with hands-on experience, responses of mid-test.
- Treatment B-Mid: Participants that started with haptic experience, responses of mid-test.
- Treatment A-Post: Participants that started with hands-on experience, responses of post-test.
- Treatment B-Post: Participants that started with haptic experience, responses of post-test.

The misconception analysis of the content required open coding to sort the data and to develop misconception’s codes, categories, and themes. To identify misconception patterns frequency count was tracked.

To determine linguistic variations on the responses the researchers used a frequency query from the NVivo 12 software. The query was restricted to 1000 most frequent words and included stemmed words.

The initial coding was also used to identify two main types of responses; responses related to density and responses related to force. Based on this analysis a decision was made to develop two separate rubrics. The next step consisted of performing axial coding to identify differences between responses. The differences between responses were then used to develop the four levels of each of the two rubrics shown in Table 5.3 and Table **??**. Both rubrics were then used to score students' responses.

The rubrics consisted of four levels of understanding. The first level of understanding, in both rubrics, implies that students responses' referred to all the variables in the system and that the interaction between them was accurately explained. The second level of understanding encompasses responses that mentioned correctly one of the variables in the system but leaves other important concepts out of the explanation. The third level of understanding was included to score responses that included references to variables related to float/sink, but are used incorrectly or the concept is inaccurate. The final level of understanding assigns a score of zero to explanations that do not mention the variables that directly intervene in the phenomenon. Refer to Table 5.3 and 5.4 for examples of each level.

Once students' responses were scored using the rubrics, descriptive statistics (mean, mode, and standard deviation) were calculated for each treatment and test. To determine if there was a significant difference between pre-test and post-test for each treatment a paired t-test with $\alpha = 0.05$ was used. Additionally, a two-sample t-test ($\alpha = 0.05$) was performed to determine if there was a significant difference between both treatments.

The rubrics consisted of four levels of understanding. The first level of understanding, in both rubrics, implies that students responses' referred to all the variables in the system and that the interaction between them was accurately explained. The second level of understanding encompasses responses that mentioned correctly one of the variables in the system but leaves other important concepts out of the explanation. The third level of understanding was included to score responses that included references to variables related to float/sink, but are used incorrectly or the concept is inaccurate. The final level of understanding assigns a score of zero to explanations that do not mention the variables that directly intervene in the phenomenon. Refer to Table 5.3 and 5.4 for examples of each level.

Table 5.3. Rubric for responses related to the density

Score	Criteria for responses related to density	Example*
3	The response presents a correct connection between the object's density and fluid's density	"If an object has a higher density than the liquid it is in it will sink if it has a lower density it will float."
2	The response makes the correct reference to density of the object but not to fluid's density or vice versa	"density. If something is very dense, it will sink. Something that doesn't have a lot of density will float."
1	The response mentions the object's density and/or fluid's density but makes the wrong connection between them or no connection at all	"I think some objects float in a liquid, while others sink because of the objects density. The more dense an object is the more likely it is to float."
0	The explanation presents important inaccuracies related to the density of the object or fluid	"Some objects are completely solid, while others aren't. Solid items can't have any air. Some are just too dense."

[*Responses from participants, the responses grammar or spelling was not altered]

Table 5.4. Rubric for responses related to forces

Score	Criteria for responses related to forces	Example*
3	The response mentions the correct role of buoyancy and gravity in the system.	"Objects have a different buoyancy because of the density of the object and of the fluid. When the object is placed in the liquid, buoyant force pushes up, while gravity pushes the object down. The densities of the object and liquid determine buoyancy."
2	The response mentions the correct role buoyancy but not gravity or vice versa	"Some objects float because of boyancy, so the force pushing the object up is grater than the force the object is pushing down."
1	The response mentions the incorrect role buoyancy and/or gravity in the system.	"The force of the object is either greater or less than the fluids' force."
0	The explanation presents important inaccuracies related to the forces acting in the system	"Because of the buoyant force acting on the object depending on the objects mass."

[*Responses from participants, the responses grammar or spelling was not altered]

5.3 Results

5.3.1 Buoyancy content knowledge assessment

The nested factorial analysis of *Buoyancy I*, refer to Table 5.5, showed that there was a significant difference between assessment scores. However, both treatments behaved similarly (please refer to Figure 5.6).

Table 5.5. Nested Factorial Analysis for Buoyancy I.

Source	F Ratio	p-value
Treatment	0.0046	0.9460
Test	9.7609	0.0001*
Test x Treatment	0.5075	0.6036

(*) indicates that the p-value ≤ 0.05.

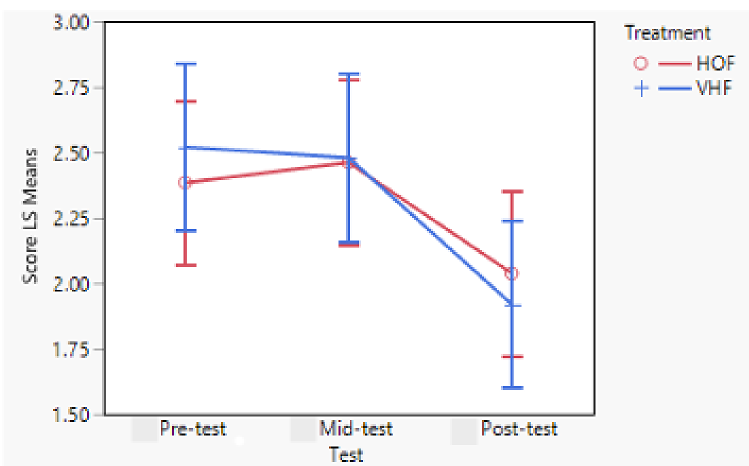


Figure 5.6. Least square means by assessment for *Buoyancy I* treatments.

The nested factorial analysis of *Buoyancy II* showed no significant difference between treatments or data collections, please refer to Table 5.6. Figure 5.7 participants in both treatments achieved similar scores in the pre, post, and delayed post assessments.

Table 5.6. Nested Factorial Analysis for Buoyancy II.

Source	F Ratio	p-value
Treatment	0.0709	0.7912
Test	0.9563	0.3879
Test x Treatment	0.0631	0.9389

(*) indicates that the p-value ≤ 0.05.

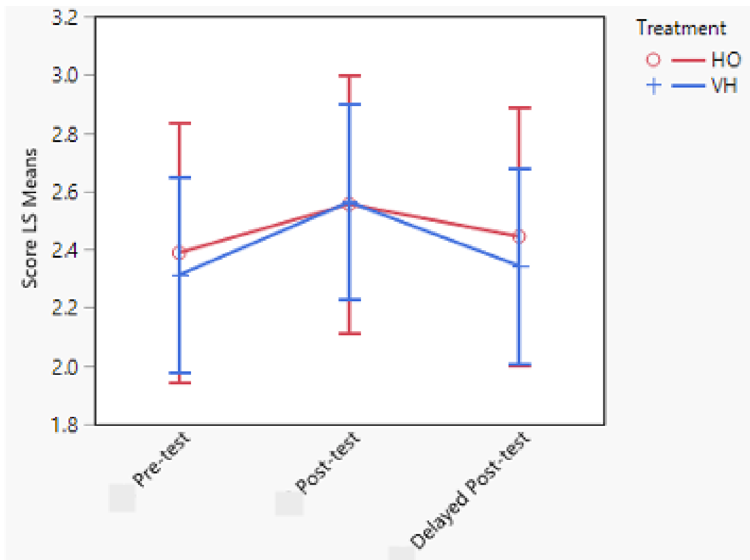


Figure 5.7. Least square means by assessment for *Buoyancy II* treatments.

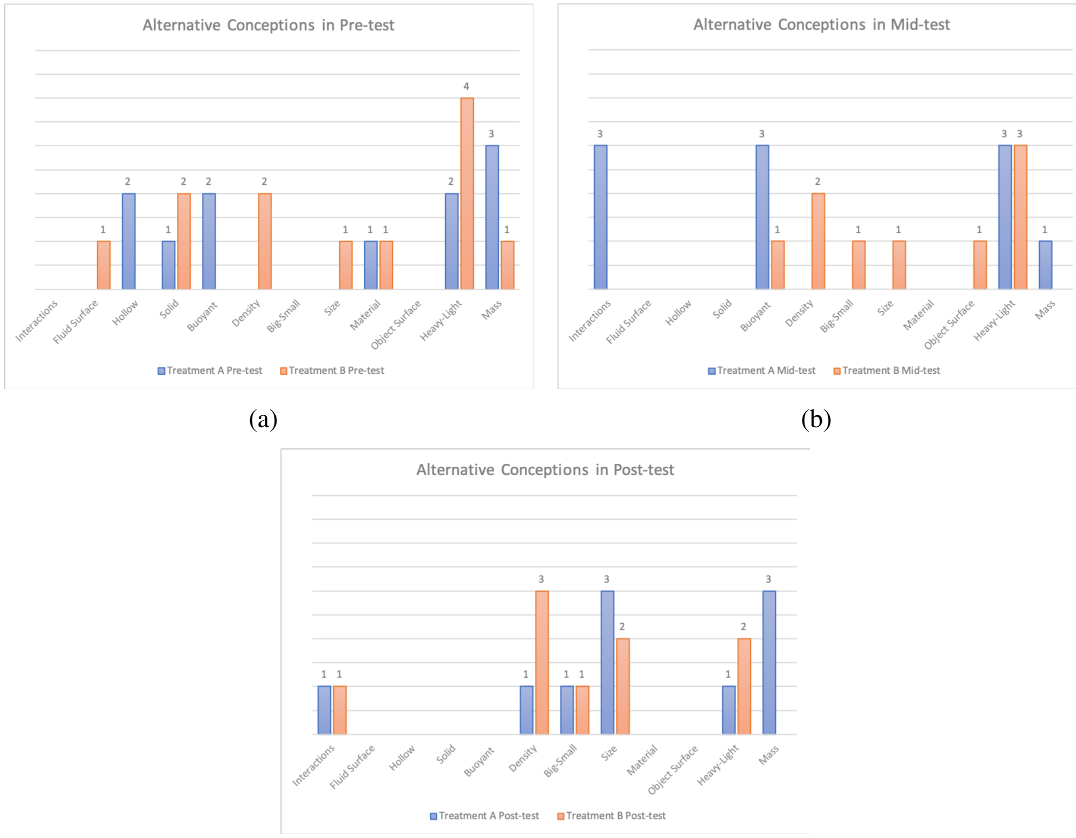
5.3.2 Misconceptions

Three main groups of misconceptions emerged from the coding of the responses to the open-ended question: “Please provide an explanation of why you think some objects float in a liquid, while others sink. You may use diagrams if you wish. Please try to be as scientific as you can in your explanation.”

The themes derived were system, fluid, and object. The first set of misconceptions are related to the forces acting on the system. The other themes encompass misconceptions related to fluid and object properties. Table 5.7 shows in detail the results of the axial codding.

Table 5.7. Themes, categories, and codes for misconceptions

Theme	Category	Code	Definition	Example
System	Forces	Interactions	The forces interactions acting in the system are not accurate	"Some float because they are lighter and smaller some sink because they are heavier and bigger. It depends on how much force is being applied "
Fluid	Surface		The liquid's surface tension named as one of the factors contributing to the phenomena	"Some liquids have a thicker, stronger surface tension which can withhold heavier objects to float. Objects that float are also less dense."
Object	Frame	Hollow	The phenomena is attributed to the air present inside the object or as part of the material	"Some objects float and some sink do to the objects density. If an object is hollow, then it will float."
		Solid	The compact composition is signaled as a factor intervening in the object behavior	"Some objects are completely solid, while others aren't. Solid items can't have any air. Some are just too dense."
	Force	Buoyant	The definition of buoyant force is not correct	"Because of the buoyant force acting on the object depending on the objects mass "
	Density		The definition of density is not correct or the roll is not correctly explained for the phenomena	"The more dense an object is compared to the water it will float. When the object is less dense than the water, it sinks."
	Dimensions	Big-Small	The object behavior is attributed to the object's size specifically point to big or small	"If an object is bigger /heavier it will sink because the density is more than the density of the water if an object is smaller/lighter it will float because it has less density than the liquid. "
		Size	The object behavior is attributed to the object's size	"Objects are based on size + density, if you are in a situation where the liquid is dense, the object will float. "
	Material		The object's material is signaled as a factor affecting the phenomena	"If the material made out of is light it will float, if it is a heavy object it wont "
	Surface		The object's surface area is named as a factor affecting the object's behavior	"Objects that float have more surface area, and are less dense than the liquid they are in."
	Weight	Heavy-Light	The object's mass is attributed to the object's behavior, heavy or light is mention	"Some float because they are lighter and smaller some sink because they are heavier and bigger."
		Mass	The object's mass is attributed to the object's behavior	"Some objects float because their mass is greater than that of the liquid it is floating in "



(a) (b)

(c)

Figure 5.8. Alternative conceptions frequency of appearance for (a) pre-test, (b) mid-test, and (c) post-test.

The majority of the misconceptions found were related to the object properties, only a small proportion related to system or fluid. Of the 55 misconceptions found a 21,15% corresponded to Treatment A pre-test responses, 23.08% to Treatment B pre-test responses, 19.23% to Treatment A mid-test, 17.31% to Treatment B mid-test, 19.23% to the Treatment A post-test, and 17.31% to the Treatment B post-test responses.

All the misconceptions found on the Treatment A were related to the object. On the haptic first group, the pretest responses were 4.33% related to fluid and 95.67% to the object. The responses to the mid-test showed that for the hands-on first 30% akin the system and 70% to the object, while in the Treatment B 100% were characterized as object-related. Finally, in the post-test Treatment A and Treatment B groups displayed 10% and 11.11%

system misconceptions respectively and 90% and 88.89% object-related misconceptions. The analyses of frequencies showed that the misconception object misconceptions of “Heavy-Light” are the most frequent and appeared in the pre-test, mid-test, and post-test responses. Figure 5.8 shows the frequencies found for each coded misconception.

5.3.3 Conceptual learning

The analysis of the descriptive statistics (refer to Table 5.8) shows a gain of 0.6 on the mean score for the physical hands-on treatment from pre-test to post-test and 0.92 for the visuo-haptic simulation group.

Table 5.8. General statistics for treatments

	Pre-test			Post-test		
Treatment	Mean	Mode	sd	Mean	Mode	sd
Physical Hands-on	1.4	0	1.2	2	3	1.1
Visuo-haptic Simulation	1.2	1	1.1	2.12	3	1.1

[sd=Standard Deviation]

5.3.4 Student Learning Gains per Treatment

The paired t-test showed that there is a significant difference between pre-test and post-test scores for each of the treatment groups (refer to Table 5.9).

Table 5.9. Paired t-test for treatments

Treatment	N	df	p-value
Physical Hands-on	26	25	0.0085
Visuo-haptic Simulation	25	24	0.009

[N=number of observations, df=degrees of freedom]

5.3.5 Comparison Between Treatments

The two-sample t-test output was a p-value of 0.7018, thus there is not enough evidence to reject the null hypothesis. In other words, there is no significant difference between the scores of the buoyancy physical hands-on experiment and the visuo-haptic simulation experiment.

5.3.6 Linguistic Variations

In Treatment A the word density (includes densities and density) is increasingly used after each activity. Between the mid-test and the pre-test, the increase is 1.14%, between the post-test and mid-test there is a difference of 9.65%. Additionally, the participants increased the use of the word force (include force and forces) from pre-test to mid-test on 2.57%. However, the use of force decreases between the post-test and the mid-test in 1.61%. Finally, the use of the word liquid (includes liquid and liquids) and objects (includes object, objects, and objects') increases after each activity.

Treatment B the utilization of the word density increases a 3.74% from pre-test to mid-test, but decreases 0.91% at the post-test. The word force was not used at all in the pre-test stage, at the mid-test there was an increment of 3.68%, but at the post-test there was a decrease of 1.56%. Finally, the utilization of the word liquid increased after each activity. But, the word object usage increased 2.81% in the mid-test and decreased 1.11% at the post-test. The results of the frequency analysis are summarized in Table 5.10. The percentages were calculated based on the frequency of repetition of a word in a pool of 1000 words.

5.4 Summary of Findings

- Sequencing hands-on/visuo-haptic simulation or visuo-haptic simulation/hands-on generates the same behavior on conceptual knowledge. In both cases, mid-test scores raised to the highest value after the first interaction.
- Only visuo-haptic simulation or hands-on tasks do not generate changes in the conceptual knowledge about buoyancy.
- Misconceptions relater to object characteristics prevail over misconceptions related to forces interacting in the system and fluid characteristics.
- Interaction with treatments reduced misconceptions appearance.
- Language patterns were found to be different for both treatments.

Table 5.10. Word's frequency by treatment

	Treatment A			Treatment B		
Word	Pre-test[%]	Mid-test [%]	Post-test [%]	Pre-test [%]	Mid-test [%]	Post-test [%]
Dense	4.92	6.59	4.10	4.48	3.34	3.81
Density (densities, density)	7.65	8.79	18.44	10.31	14.05	13.14
Float (float, floating, floats)	8.74	6.94	8.20	10.76	8.03	9.75
Force(force, forces)	1.09	3.66	2.05	0	3.68	2.12
Greater	1.09	2.56	2.46	0.90	2.68	2.12
Less	4.92	5.86	3.69	4.04	4.35	3.81
Liquid (liquid,liquids)	7.65	11.72	13.11	6.73	11.04	13.56
Object (object, objects, objects')	14.21	16.12	19.67	15.25	18.06	16.95
Sink (sink,sinks)	6.56	4.40	5.74	9.42	5.35	6.78
Small (small, smaller)	0	0.73	1.23	0.45	1	2.12
Water	2.73	0.73	2.05	3.14	2.68	0
Mass	3.28	2.93	1.64	0	1.67	0.85

CHAPTER 6. DISCUSSION AND IMPLICATIONS

The sense of touch enables perception and interaction of physical objects, however, most digital learning environments depend uniquely or mainly on vision for transmitting information (Thurfjell, McLaughlin, Mattsson, & Lammertse, 2002). The use of haptic interfaces in learning settings can enable motor exploration of concepts in textbooks (Comai & Mazza, 2010). Force feedback, created by haptic interfaces, facilitates the feeling of touching objects when interacting with virtual environments (Thurfjell et al., 2002). A novel way of examination is available when haptic technology is incorporated into the learning environment (Lederman & Klatzky, 1987).

Data analysis of the *Electricity and Magnetism* experiments yielded inconclusive results. On one side, the quantitative analysis showed that there was gain in content knowledge for all experiments and treatments (Tables 4.6, 4.7, 4.8, 4.9, and 4.10). The *Electricity and Magnetism* experiments implemented a control group that was visually-enhanced only with no haptic feedback (V) and the following experimental conditions respectively: I (H1) haptic-enhanced only with minimal visual cues, II (H2 $\longrightarrow$ H2+V2) haptic-enhanced only with minimal visual cues followed by visual cues activation, III (H3 $\longrightarrow$ H3+V3) haptic-enhanced only with minimal visual cues followed by visual cues activation, IV (H4+V4) visually-enhanced and haptic feedback simultaneously, and V (H5 $\longrightarrow$ H5+V5) haptic-enhanced only with minimal visual cues followed by visual cues activation (please refer to Table4.1 for details of every experiment). However, even though all control and experimental treatments increased their mean, a significant difference between pre-test and post-test scores was only found for experimental treatments I (1.8421-2.7368), II (1.0435-2.2609), V (1.300-2.150) and for the control treatment III (1.619-2.143). Furthermore, no significant difference was found when post-test scores of control and experimental treatments were contrasted within all experiments (Table 4.13). Finally, the analysis of the experiments that included delayed post-test in their data collections (I,II, and IV), showed that there was not a significant difference in the scores behavior for any treatment (Table 4.14, 4.16, and 4.18). That is, for the three experiments, both treatments decreased their mean in contrast to their post-test but not to the level of the pre-test means. These results contradict previous research in the field of haptics in learning, such as the one carried by Hallman, Paley, Han, and Black (2009) who reported statistical significant change on participants conceptual knowledge about gears when a visuo-haptic simulation was used for instruction over participants using a purely visual simulation. However, electricity and magnetism is a phenomenon that cannot be experienced or even observed in contrast to gears that are tangible objects. Han and Black (2011) considered that tacit knowledge acquired by students' bodily interactions with objects allowed them to make direct predictions and judgments.

On the other hand, the qualitative analysis of *Electricity and Magnetism* I (single modality), II (sequenced modality), and IV (dual modality), showed that only the sequential modality presented a statistical difference in the scores between pre-scores and post-scores, and the gain was maintained two weeks later (Table 4.23 and Figure 4.9(b)). The qualitative results agree with Reiner (1999), who reported that after interaction with visuo-haptic simulations learners were able to draw naive scientific representations of vectors, forces, and fields. Han and Black (2011) suggested that the enrichment of the multimodal virtual environments with haptic feedback either as force feedback or kinesthetic movement can facilitate information encoding and creation of multimodal representations of abstract phenomena. A positive significant effect of haptically-enhanced learning environments was also reported by Civelek, Ucar, Ustunel, and Aydın (2014), who used open-ended questions to measure conceptual knowledge about gravitational force.

During the analysis of graphical representations, the strength of force vs. distance from a point charge, the participants in the experimental treatments identified two correct representations: one discrete and one continuous (Figure 4.11); and four alternative representations: two directly proportional and two inversely proportional (Figure 4.12). These graphical representations represented participants' mental models of the effect of distance in the force. Mental models are created by processing one or numerous external representations and based on existing knowledge (Millet, Lécuyer, Burkhardt, Haliyo, & Regnier, 2013). Figure 4.10 shows that the majority of participants using haptic feedback with minimal visual cues drew incorrect relationships, and the addition of rich visual cues did not significantly increase the number of correct representations. The results suggest that once an alternative conception was created, it was difficult to change, even when adding reach visual cues. The results in this study reinforce the results reported by Magana and Balachandran (2017a) who indicated that participants using visuo-haptic simulations in electromagnetism were able to accurately represent forces around the field.

The analysis of the *Buoyancy* experiments results suggest that both treatments (Physical Hands-on, Visuo-haptic Simulation) can be equally effective in helping students learn about buoyancy. These results are similar to the ones obtained by Minogue and Borland (2016) and Young et al. (2011) when compared haptically-enhanced simulations (visuo-haptic simulations) with visual simulations. However, both treatments were successful in terms of increasing the score from the pre-test to the post-test. This evidence support the belief that real physical haptic stimuli and simulated haptic stimuli can positively impact educational instruction about buoyancy. This result has practical significance given that hands-on activities are believed to be essential in science education (Butts, Hofman, & Anderson, 1993).

Results suggest that the use of visuo-haptic simulations can equally support embodied learning through experimentation. The observations in this work align with Biocca, Kim, and Choi (2001) who stated that presence is created by multimodal integration of cues. However, from a practical point of view, visuo-haptic simulations can be more efficient. For instance, for the case of the educational hands-on activities prepared for this study, they required a great amount of preparation in addition to the need for having at least two assistants who cleaned the materials to reuse them for the following session. On the other hand, the visuo-haptic simulation experiment was easily reproduced for a large audience for consecutive sessions after installing the simulation and the haptic device. The results obtained in the *Electricity and Magnetism* and *Buoyancy* experiments were not conclusive, thus agreeing with (Zacharia, 2015), who suggested that the addition of haptic feedback did not necessarily generate conceptual knowledge representing an advantage over traditional computer simulations. However, findings from the series of studies performed as part of this dissertation suggest that the incorporation of haptic feedback into learning environments can provide an embodied grounding experience to create intuitive knowledge and multimodal representation of abstract phenomena.

Alternative conceptions were observed in Treatment A (visuo-haptic simulation followed by physical hands-on) and B (physical hands-on followed by visuo-haptic simulation). In Treatment A in the pre-test, six codes were identified; after the interaction with the visuo-haptic simulation four codes were present; lastly, after the physical hands-on, six codes were prevalent. On the other hand, in treatment B seven codes were identified in the pre-test; six in the mid-test; and five (5) in the post-test. Taking in to account only the frequency of appearance of alternative conceptions, Treatment B was the more effective sequence for decreasing alternative conceptions. This study found that such alternative conceptions were related to the “object’s properties”, which have also been identified by Yin et al. (2008) and Rowell and Dawson (1977). In both cases, the specific misconception related to mass and weight seemed to be the most difficult to tackle, even with the support of hands-on activities. In the case of alternative conceptions related to the ”acting forces” on the system, mass and weight persisted as the primary source of confusion. This result is congruent with the misconceptions related to buoyancy detailed by Pantazopoulou and Skoumios (2012).

6.1 Implications for Teaching and Learning

Lectures have prevailed as the main form of instruction in tertiary education, despite the benefits entailed by student self-constructed understanding (Freeman et al., 2014). Freeman et al. (2014) reported that active learning instruction can increase performance across all STEM fields, despite the class size, complexity level, or subject type. Additionally, as reported in meta-analysis in the use of simulations for STEM learning, simulations allow students to experience scientific phenomena that may be difficult or impossible to replicate with equipment (DAngelo et al., 2014).

Johnson-Glenberg et al. (2014), suggested that learning gains generated by boosting embodiment can not necessarily be assessed using standard test. This may explain the conflicting results of the qualitative and quantitative analysis in the *Electricity and Magnetism* experiments. Relevant learning gains where found when participants were asked to draw what they thought would happen under specific conditions. On the other hand, no learning gain was detected when using multiple-choice questions that depicted complex theoretical concepts. The motoric and spatial knowledge generated by the embodied activity may be difficult to explain or convey in words (Johnson-Glenberg et al., 2014).

Results obtained in the *Buoyancy* experiments suggest that inclusion of haptic feedback fostered the construction of appropriate mental models, by eliminating misconceptions, of abstract phenomena. Chan and Black (2006), recommended that multimedia-based instruction should support the construction of central mental models rather than detailed structures. Haptic feedback provides additional information for students to reason about fundamental relationships and interactions existent in the system (Chan & Black, 2006).

Enrichment of learning environments with sensory stimuli, such as touch, can elicit in the learner sensory curiosity (Ciampa, 2014). Additionally, haptic feedback can also evoke cognitive curiosity by helping learners to discover inconsistent knowledge (Ciampa, 2014). To improve learning, cognitive load theory suggests discarding unnecessary taxing cognitive tasks (Clark & Jorde, 2004). Information retained in the working memory at a given time can be reduced using external cognitive resulting cognitive offloading (Clark & Jorde, 2004).

The usually invisible, non-tangible, abstract, or counter-intuitive nature of complex concepts in science may explain the appearance of alternative conceptions (Magana & Balachandran, 2017b). The qualitative analysis of *Electrostatics Graphical Representation* showed that only students in the visual rich control treatments (V1, V2, and V4) adopted in their model the alternative conception of force towards them at the center of the charged ring representation. On the other hand, none of the students in contact with any modality that included haptic feedback adopted this alternative conception. The simulation allowed visual rich control treatments (V1, V2, and V4) to move freely around the charged ring, conversely, haptic feedback restricted mobility based on scientific knowledge of charge behavior. Zirbel (2004) stated that alternative conceptions are extremely resistant to change, making the results far more meaningful.

Conceptual change occurs when students are exposed to accurate scientific concepts. Specifically, when conceptual change happens students tend to trade their alternative or incomplete conceptions to incorporate the more credible concepts (Cobern, 1996). The phenomenon of buoyancy is observable and most people had experienced it before (i.e. played with toys in a tub, observed boats floating). Cobern (1996) stated that everyday conceptions are different from scientific ones because they are used in other contexts and that for creating scientific conceptions it is necessary to disrupt students' natural interpretations of the concepts.

The qualitative analysis of the *Electricity and Magnetism* worksheets for the Experiments I, II, and IV for the experimental condition revealed that some of the participants that created incorrect drawings perceived the relationship as linear. This suggests that the force feedback at each comparison point (A, B, and C) was not enough to create just noticeable difference (JND). Weber's Law explains that human perception is relative, and that ability to perceive changes in stimuli intensity has a linear relationship (Ozana, Berman, & Ganel, 2018; Smeets & Brenner, 2008).

6.2 Implications for the Design of Multimodal Virtual Environments

Walters (2014), stated that haptic feedback may be erroneously marketed as direct, intuitive, and unmediated. In the case of the Novint Falcon device, one of the most commercially available haptic devices, the force feedback has only one point of contact. Thurfjell et al. (2002) stated that this singular point of interaction is sufficient for determining objects characteristics even without visual input. When creating a Multimodal Virtual Learning Environment it is fundamental to consider the "probe" interaction created by the use of force feedback and how this will alter user exploration of the phenomena under study. Current commercially available haptic interfaces should consider that the interaction is bind to probe exploration.

The meaning-making, when using haptic interfaces, is closely related to user acquaintance with the technology and manipulation practices (Walters, 2014). The user will need to repetitively probe to examine a certain phenomenon (Jones, Minogue, Tretter, et al., 2006). In the present study, visuo-haptic simulations were accompanied by rich visualizations. This feature was also diminished in the form of minimal visual cues, to support probe exploration. The novel nature of haptic feedback may deviate learners' attention from the phenomena under study. To maximize thoughtful exploration, specific tasks should be provided (Ciampa, 2014). Scaife and Rogers (1996) suggested that effective representations of phenomena require engaging learners in graphical representation tasks to avoid the construction of erroneous mental models.

Thurfjell et al. (2002) noted that the realism of digital simulations can be improved by the use of visual and haptic information. However, the results of the qualitative analysis in *Electricity and Magnetism* suggest that the use of sequenced modalities significantly improved motoring understanding of the phenomena. To provide sequenced modalities it is necessary the the MVE afford partial activation (i.e. rich visual cues, minimal visual cues) and suppression of the modalities (i.e haptic on/off).

6.3 Implications for Education Research

There has been extensive technical research for improving haptic interfaces. However, there is still a lot that we do not fully understand how to integrate haptic feedback in learning environments. It has been identified that haptic feedback coupled with simulation is an effective form of training of psychomotor skills (Van der Meijden & Schijven, 2009). Haptic feedback had been used for training in veterinary medicine (Kinnison, Forrest, Frean, & Baillie, 2009; Okamura, Basdogan, Baillie, & Harwin, 2011; Parkes, Forrest, & Baillie, 2009) , medical training (Basdogan et al., 2004; Basdogan, Ho, & Srinivasan, 2001; Escobar-Castillejos et al., 2016; Ullrich & Kuhlen, 2012), and dental tasks (Escobar-Castillejos et al., 2016; Eve et al., 2014; C. Luciano, Banerjee, & DeFanti, 2009; Wang, Liu, Zhang, Zhang, & Xiao, 2012). However, there is still inconclusive evidence on the use of haptic feedback in conjunction with simulations to support the development of cognitive knowledge, particularly in the form of conceptual learning (Zacharia, 2015).

On one hand, research suggests that information acquisition is potentiated by involving as many senses as possible in learning processes (Chittaro & Ranon, 2007). On the other hand, Lécuyer (2009) suggested that in the case of sensory conflict, between visual and haptic information, one of the senses will dominate. The sequential implementation of sensory modalities is a novel approach to improve learning environments (Magana et al., 2019). Research questions that could be explored are: (i) Does the order in which haptic and visual stimuli are sequenced impact conceptual learning of abstract concepts? (ii) Are verbal and non-verbal representations affected by sequencing the order of modalities?

The nature of the feedback that could be simulated requires further study in the context of using it for complex or abstract phenomena across different STEM concepts. In the *Electricity and Magnetism* experiments, haptic feedback was not implemented as a contradictory stimulus; rather it was used as a backup stimulus. However, interpretation if haptic stimulus was not always appropriate; thus, when visual information was presented it could have been interpreted as a source of conflict. Visual dominance in spatial interaction tasks has been shown to exist by Rock and Victor (1964) when using physical objects. Haptic dominance has also been shown to occur in tasks that require to determine an object's material, texture, and weight (Lécuyer, 2009). The study of the question QP2 in sequenced modality experiments showed that only a small proportion of participants accurately drew the relationship when they used a visuo-haptic simulation with low visual cues and did not change their responses to match the visual information later when rich visual cues were enabled. Moreover, some of these participants used incorrectly the newly available visual information to back up what they perceived haptically (Figure 4.12(a)). Research questions that could be explored are: (i) Does the number of available degrees of freedom affect conceptual knowledge acquisition for abstract concepts? (ii) Is there a best way to asses the effect of haptic feedback on conceptual knowledge? (iii) What are the characteristics of an effective visuo-haptic simulation for abstract phenomena?

Finally, visuo-haptic simulations may increase learning due to their associated levels of enjoyment. Williams II, Chen, and Seaton (2001) reported positive receptions engaging students with physics visuao-haptic simulations by high school students. Furthermore, Civelek et al. (2014) described a positive effect on learners' motivation and encouragement towards physics when using VR environments enhanced with force feedback. Further research is needed on the role of enjoyment while interacting with visuo-haptic simulations and the relationship between levels of enjoyment and learning. Research questions that could be explored are: (i) Is presence affected by the sequencing of haptic and visual stimuli? (ii) Does enjoyment of visuo-haptic simulations manipulation translate into enjoyment of the concept under study?

6.4 Summary

The purpose of the present study was to examine the effect of adding haptic feedback for promoting the learning of abstract phenomena. Specifically, this study investigated if adding haptic feedback in the form of visuo-haptic simulations (in single, dual simultaneous, and sequenced modalities) would provide a learning advantage on the topics of *Electricity and Magnetism* and *Buoyancy*, over traditional simulations. Data analysis yielded inconclusive results, suggesting that both methods were equally effective. However, under specific circumstances, Multimodal Virtual Environment enriched with haptic feedback can create lasting conceptual knowledge about the topic.

Based on the findings of this work, this chapter presents implications for teaching and learning, design of Multimodal Virtual Environment, and research were presented in this chapter.

CHAPTER 7. CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

In this work, visuo-haptic simulations were presented as alternative tools to traditional computer simulations for learning abstract and/or complex physics concepts. Using commercially available haptic devices the researcher implemented learning environments that aimed to teach *Electricity and Magnetism* and *Buoyancy* concepts. The results presented in this study contribute insights on the use of haptic technology for learning environments and especially on educational representations of abstract and complex phenomena.

The two types of data analysis performed for this study yielded inconclusive results. On the one hand, the quantitative analysis of the *Electricity and Magnetism* indicated that the availability of tactile stimulus pass a positive effect on concept knowledge acquisition, but it was not statistically different from the gain achieved by purely visual simulations. That is, single, dual, and sequenced learning modalities quantitatively performed similarly in the gain of conceptual knowledge of *Electricity and Magnetism*. However, based on the *Electricity and Magnetism* qualitative analysis, it can be concluded that the implementation of haptic feedback had a greater impact on learning outcomes when it's integration was sequential. Additionally, participants in any of the visuo-haptic simulations conditions and within any modality, performed significantly better in non-verbal assessments when compared to verbal evaluations. On the other hand, the quantitative experiments carried out in the topic of *Buoyancy* showed that physical activities were as equally effective as visuo-haptic simulations. However, the qualitative analysis revealed several alternative conceptions of the phenomenon. Alternative conceptions related to the object seemed to be particularly hard to change. In conclusion, haptic feedback has shown promise as a useful resource for simulation enrichment and creation of presence. However, there are still many questions regarding how students perceive, accommodate, and learn from haptic interfaces. Whit the increasing use of technology-based learning environments it is important to continue performing research in this field, to maximize learning outcomes.

The results of this study had limitations regarding the population samples. Moreover, learning sessions using visuo-haptic simulations were bound to a single time. Lastly, the integration of haptic feedback was bound to the capabilities if a commercially available device. Therefore, future work should include (a) thorough testing of the visuo-haptic simulation with different populations, (b) improving the alignment between the experiences during the learning activity and the assessment forms, (c) use of validated assessments testing on common alternative conceptions found in this study; and (d) longitudinal studies to determine the long term impact of the integration of haptic feedback in *Electricity and Magnetism* and *Buoyancy* instruction. Finally, a pressing subject of study in multimodal virtual environments would be to identify a set of best practices when using haptic feedback to enhance simulations.

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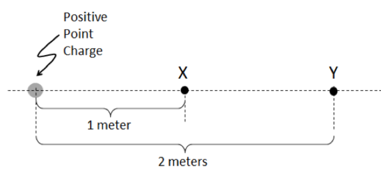
APPENDIX A. ELECTRICITY AND MAGNETISM ASSESSMENTS

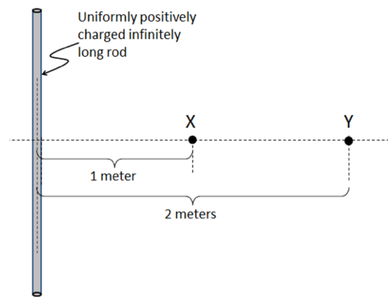
A.1 Pre-test, post-test, and delayed post-test version 1

1. A **positive point charge** is shown below. How does the electrical force on a positive test charge placed at Y (2 meters away) compare with the electrical force on the same positive test charge if it were placed at X (1 meter away)?



   (a) Force on test charge placed at Y is **FOUR TIMES** the force on test charge placed at X.
   (b) Force on test charge placed at Y is **TWICE** the force on test charge placed at X.
   (c) Force on test charge placed at Y is **EQUAL TO** the force on test charge placed at X.
   (d) Force on test charge placed at Y is **ONE HALF** the force on test charge placed at X.
   (e) Force on test charge placed at Y is **ONE FOURTH** the force on test charge placed at X.

2. A uniformly positively charged infinitely long rod is shown below. How does the electrical force on a positive test charge placed at Y (2 meters away) compare with the electrical force on the same positive test charge if it were placed at X (1 meter away)?
   (a) Force on test charge placed at Y is **FOUR TIMES** the force on test charge placed at X.
   (b) Force on test charge placed at Y is **TWICE** the force on test charge placed at X.

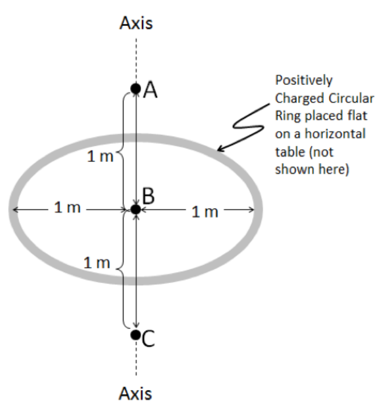


(c) Force on test charge placed at Y is **EQUAL TO** the force on test charge placed at X.

(d) Force on test charge placed at Y is **ONE HALF** the force on test charge placed at X.

(e) Force on test charge placed at Y is **ONE FOURTH** the force on test charge placed at X.

3. A uniformly positively charged circular ring of radius 1 meter is lying flat on a horizontal table (not shown in figure). The axis of the ring is a vertical line which passes through the center of the ring, extending indefinitely above and below the table. Where should a positive test charge be placed such that it experiences ZERO force due to the charges on the ring?



(a) At point **A**, on the axis of the ring, but **1** meter above the table.

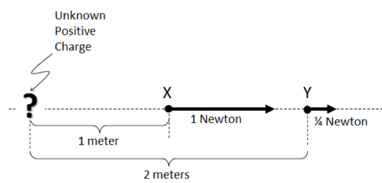
(b) At point **B**, **exactly at the center** of the ring.

(c) At point **C**, on the axis of the ring, but **1 meter below** the table.

(d) **Anywhere along the axis** of the ring.

(e) None of the above

4. You place a positive test charge at Point **X** which is **1 meter** away from the unknown charge (**?**) and experience a force of **1 Newton**. You move to location **Y**, which is **2 meters** away from the unknown charge (**?**) and experience a force of **1/4 Newton**. Based on this information, what kind of charge is the unknown charge?



(a) **POINT** charge

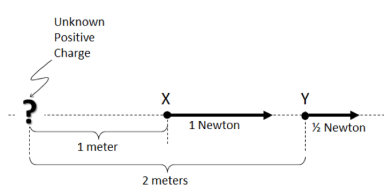
(b) **INFINITE LINE** charge

(c) **RING** charge

(d) There is **insufficient information** to answer this question.

(e) None of the above.

5. You place a positive test charge at Point **X** which is **1 meter** away from the unknown charge (**?**) and experience a force of 1 Newton. You move to location **Y**, which is **2 meters** away from the unknown charge (**?**) and experience a force of **1/2 Newton**. Based on this information, what kind of charge is the unknown charge?



(a) **POINT** charge

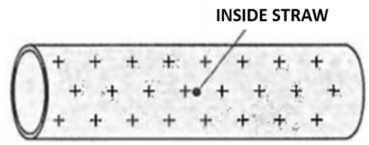
(b) **INFINITE LINE** charge

(c) **RING** charge

(d) There is **insufficient information** to answer this question.

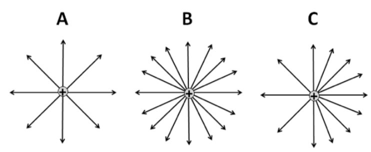
(e) None of the above.

6. A very **long hollow soda straw** is uniformly charged. What is the force experienced by a point charge that is placed inside at the center the straw?



   (a) **ZERO**.
   (b) A non-zero force pointing to the **LEFT**.
   (c) A non-zero force pointing to the **RIGHT**.
   (d) A non-zero force pointing **UPWARD**.
   (e) A non-zero force pointing **DOWNWARD**.

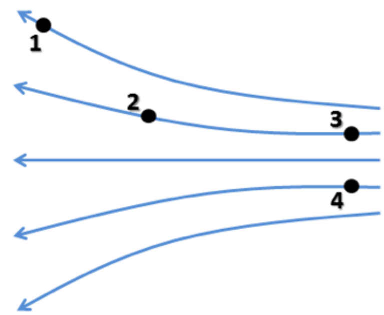
7. Several electric field line patterns due to a **positive point charge** are shown. Which of these patterns is **INCORRECT**?



   (a) Diagram **A**.
   (b) Diagram **B**.
   (c) Diagram **C**.
   (d) Diagram **A and B**.
   (e) Diagram **B and C**.

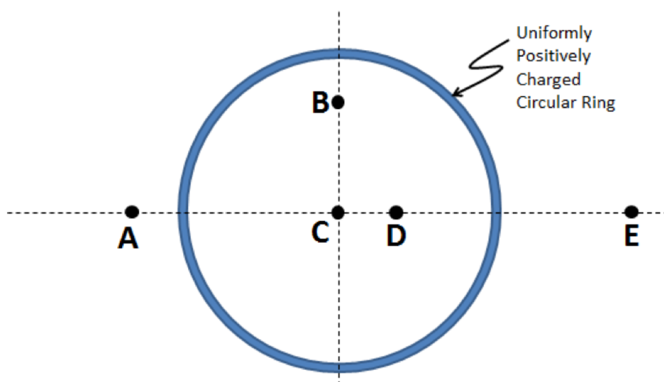
8. The electric field lines are shown in the diagram. How does the force experienced by a positive test charge placed at points 1, 2, 3 or 4 compare with each other?

   (a) Force at 1 $<$ Force at 2 $<$ Force at 3 = Force at 4.
   (b) Force at 4 = Force at 3 $<$ Force at 2 $<$ Force at 1.
   (c) Force at 1 $<$ Force at 2 = Force at 3 $<$ Force at 4.
   (d) Force at 4 $<$ Force at 3 = Force at 2 $<$ Force at 1.



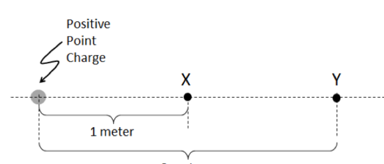
(e) None of the above.

9. A **uniformly positively charged ring** is shown below. Draw arrows representing the force experienced by a **positive test charge placed** at points **A, B, C, D, and E**. The direction of each arrow should represent the direction of the force. The length of each arrow should represent the strength of the force at that point.



<u>A.2 Pre-test, post-test, and delayed post-test version 2</u>

1. A **positive point charge** is shown below. How does the electrical force on a positive test charge placed at Y (2 meters away) compare with the electrical force on the same positive test charge if it were placed at X (1 meter away)?



(a) Force on test charge placed at Y is **FOUR TIMES** the force on test charge placed at X.

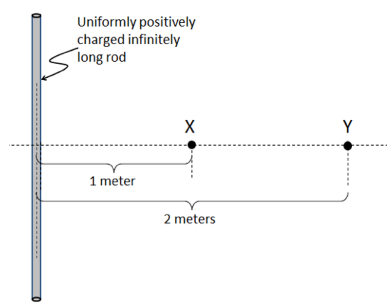
(b) Force on test charge placed at Y is **TWICE** the force on test charge placed at X.

(c) Force on test charge placed at Y is **EQUAL TO** the force on test charge placed at X.

(d) Force on test charge placed at Y is **ONE HALF** the force on test charge placed at X.

(e) Force on test charge placed at Y is **ONE FOURTH** the force on test charge placed at X.

2. A **uniformly positively charged infinitely long rod** is shown below. How does the electrical force on a positive test charge placed at Y (2 meters away) compare with the electrical force on the same positive test charge if it were placed at X (1 meter away)?



(a) Force on test charge placed at Y is **FOUR TIMES** the force on test charge placed at X.

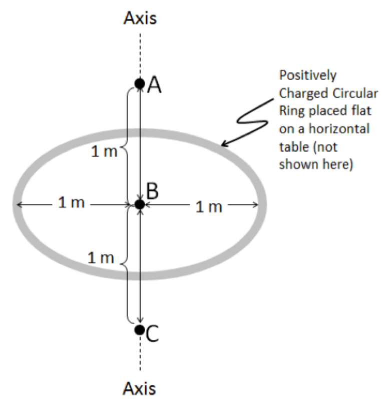
(b) Force on test charge placed at Y is **TWICE** the force on test charge placed at X.

(c) Force on test charge placed at Y is **EQUAL TO** the force on test charge placed at X.

(d) Force on test charge placed at Y is **ONE HALF** the force on test charge placed at X.

(e) Force on test charge placed at Y is **ONE FOURTH** the force on test charge placed at X.

3. A uniformly positively charged circular ring of radius 1 meter is lying flat on a horizontal table (not shown in figure). The axis of the ring is a vertical line which passes through the center of the ring, extending indefinitely above and below the table. Where should a positive test charge be placed such that it experiences ZERO force due to the charges on the ring?



(a) At point **A**, on the axis of the ring, but **1** meter above the table.

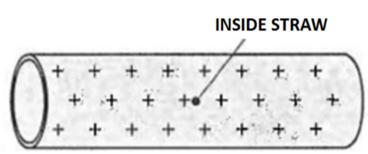
(b) At point **B**, **exactly at the center** of the ring.

(c) At point **C**, on the axis of the ring, but **1 meter below** the table.

(d) **Anywhere along the axis** of the ring.

(e) None of the above

4. A very **long hollow soda straw** is uniformly charged. What is the force experienced by a point charge that is placed inside at the center the straw?



(a) **ZERO**.

(b) A non-zero force pointing to the **LEFT**.

(c) A non-zero force pointing to the **RIGHT**.

(d) A non-zero force pointing **UPWARD**.

(e) A non-zero force pointing **DOWNWARD**.

5. In the figure, positive charges q2 and q3 exert on charge q1 a net electric force that points along the +x axis. If a positive charge Q is added at (b,0), what now will happen to the force on q1? (All charges are fixed at their location).

(a) No change in the size of the net force since Q is on the x-axis.

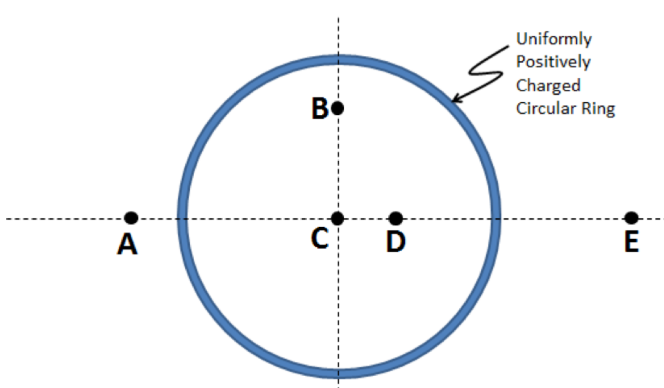
(b) The size of the net force will change but not the direction.

(c) The net force will decrease and the direction may change because of the interaction between Q and the positive charges q2 and q3.

(d) The net force will increase and the direction may change because of the interaction between Q and the positive charges q2 and q3.

(e) Cannot determine without knowing the magnitude of q1 and/or Q.

6. A **uniformly positively charged ring** is shown below. Draw arrows representing the force experienced by a **positive test charge placed** at points **A, B, C, D, and E**. The direction of each arrow should represent the direction of the force. The length of each arrow should represent the strength of the force at that point.



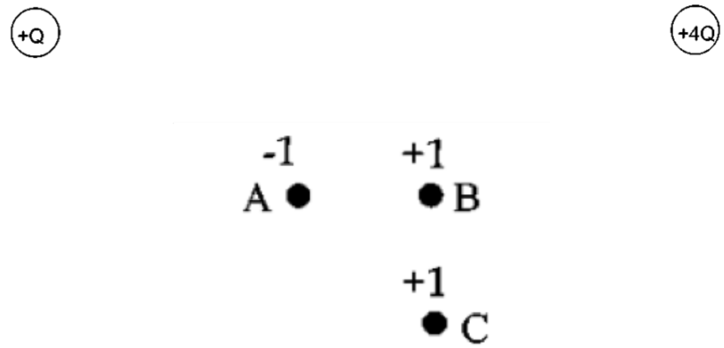
A.3 Transfer and delayed transfer tests

For questions 1-3: Two small objects each with a net charge of +Q exert a force of magnitude F on each other.

We replace one of the objects with another whose net charge if +4Q

1. The original magnitude of the force on the +Q charge was F; what is the magnitude of the force on +Q now?
   (a) 16F
   (b) 4F
   (c) F
   (d) F/4
   (e) other
2. What is the magnitude of force on the +4Q charge?
   (a) 16F
   (b) 4F
   (c) F
   (d) F/4
   (e) other

   Next we move the +Q and +4Q charges 3 times as far apart as they were:
3. Now, what is the magnitude of the force on the +4Q?



(a) F/9

(b) F/3

(c) 4F/9

(d) 4F/3

(e) other

4. Which of the arrows is in the direction of the net force on charge B?

(a) ↙

(b) ↗

(c) ⟵

(d) ↑

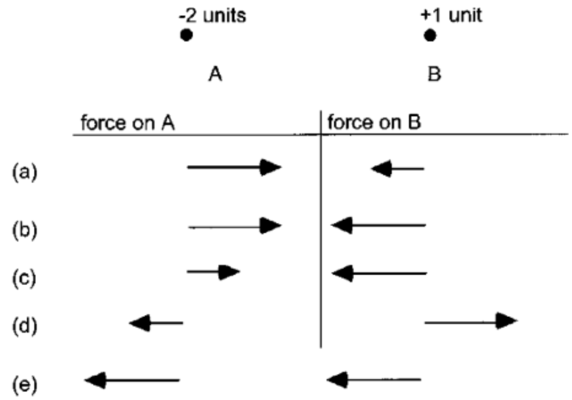
(e) None of these

5. The picture below shows a particle (labeled B) which has a net electric charge of +1 unit. Several centimeters to the left is another particle (labeled A) which has a net charge of -2 units. Choose the pair of force vectors (the arrows) that correctly compare the electric force on A (caused by B) with the electric force on B (caused by A).

6. In the figure, positive charges q2 and q3 exert on charge q1 a net electric force that points along the +x axis. If a positive charge Q is added at (b,0), what now will happen to the force on q1? (All charges are fixed at their location).

(a) No change in the size of the net force since Q is on the x-axis.

(b) The size of the net force will change but not the direction.



(c) The net force will decrease and the direction may change because of the interaction between Q and the positive charges q2 and q3.

(d) The net force will increase and the direction may change because of the interaction between Q and the positive charges q2 and q3.

(e) Cannot determine without knowing the magnitude of q1 and/or Q.

7. In the figure below, the electric field at point P is directed upward along the y-axis. If a negative charge Q is added at a point on the positive y-axis, what happens to the field at P? (All of the charges are fixed in position)

(a) Nothing since Q is on the y-axis.

(b) Strength will increase because Q is negative.

(c) Strength will decrease and the direction may change because of the interactions between Q and the two negative qs.

(d) Strength will increase and the direction may change because of the interactions between Q and the two negative qs.

(e) Cannot determine without knowing the forces Q exerts on the two negative qs.

8. A positive charge is placed at rest at the center of a region of space in which there is a uniform, three-dimensional electric field. (A uniform field is one whose strength and direction are the same at all points within the region.) When the positive charge is released from rest in the uniform electric field, what will its subsequent motion be?

    (a) It will move at a constant speed.

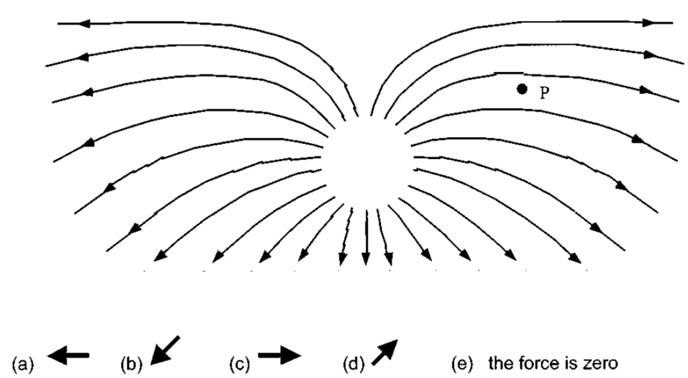
    (b) It will move at a constant velocity.

    (c) It will move at a constant acceleration.

    (d) It will move with a linearly changing acceleration.

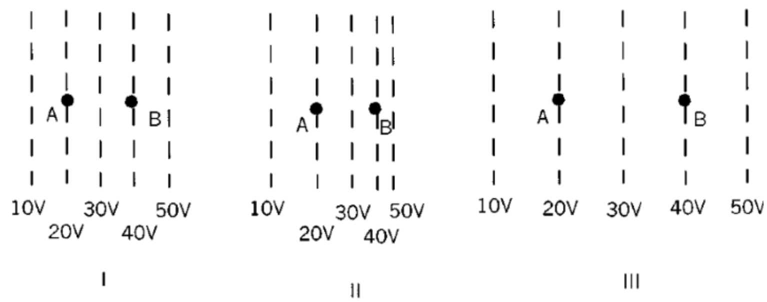
    (e) It will remain at rest in its initial position.

9. What is the direction of electric force on a negative charge at point P in the diagram below?



10. In the figures below, the dotted lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) How does the magnitude of electric field at B compare for these three cases?

    (a) I > III > II



(b) I > II > III

(c) III > I > II

(d) II > I > III

(e) I = II = III

A.4 Treatment A and B Worksheet

In each of the programs that you run on the computer you can place the cursor of your haptic device and feel the force experienced by a positive test charge if it were to be placed at that point.

- Point charge

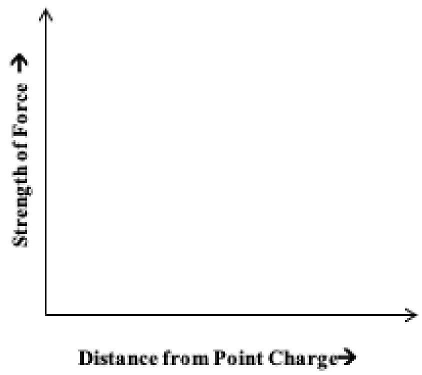
1. (Record Table Point) Place the cursor at each point **A**, then **B**, then **C**. At each point, record the information in the table below:

Point	**Distance** of point from charge (use ruler to measure it)	**Direction** of the **force experienced** by you when you place your cursor at the point. (Draw an arrow)	**Strength** of the **force** experienced by you when you place your cursor at the point (Read off value from screen)
A			
B			
C			

Based on the information you recorded above answer the questions below

2. (QP1) What is the direction of force on a **positive** test charge due to a **positive point charge** toward or away from the positive point charge?

3. (QP2) Use the data above to draw a graph of **Strength** of Force vs. **Distance from Point Charge**.



4. (QP3) Based on the graph, if you double your distance from the **point** charge, how will the strength of the force change? i.e. will it double, halve, or something else?

   Press N on your keyboard. This causes the test charge to become a negative test charge.

5. (QP4) What is the direction of force on a **negative** test charge due to a **positive point charge** toward or away from the positive point charge?

- Line charge

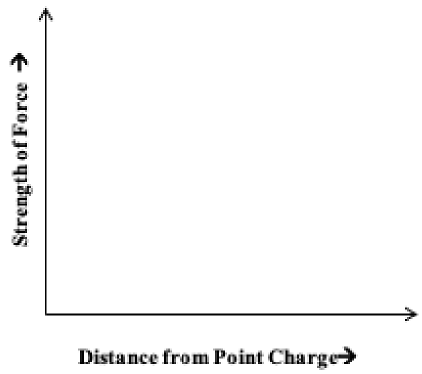
  You will see a cross section of an infinite line charge. It looks like a point charge, because you are looking at it from one end. You cannot see the depth into the screen which is infinite, because it is an infinite line charge.

1. (Record Table Line) Place the cursor at each point **A**, then **B**, then **C**. At each point, record the information in the table below:

Point	**Distance** of point from charge (use ruler to measure it)	**Direction** of the **force experienced** by you when you place your cursor at the point. (Draw an arrow)	**Strength** of the **force** experienced by you when you place your cursor at the point (Read off value from screen)
A			
B			

Based on the information you recorded above answer the questions below

2. (QL1) What is the direction of force on a **positive** test charge due to a **positive infinite line charge** toward or away from the **positive infinite line charge**?
3. (QL2) Use the data above to draw a graph of **Strength** of Force vs. **Distance from Infinite Line Charge**.



4. (QL3) Based on the graph, if you double your distance from the **infinite line** charge, how will the strength of the force change? i.e. will it double, halve, or something else?
5. (QL4) Compare the graph you sketched for the positive point charge with the positive infinite line charge.
   What are the similarities between the two graphs? Be as specific as you can.
   Press N on your keyboard. This causes the test charge to become a negative test charge.
6. (QL5) What is the direction of force on a **negative** test charge due to a **positive infinite line charge** toward or away from the positive point charge?

- Ring charge You will see a ring of charge. It is actually the cross section of an infinitely long tube of charge, but it looks like a ring because you are looking at it from one end. Like the line charge, it extends infinitely into the screen.
  - Scenario A: Move the cursor **from the center** of the ring **to point A**.
    1. (QRA1) What is the **direction** of the force you **feel**, as you move your cursor from the **center** to point **A**?

2. (QRA2) How does the **strength** of the force you **feel**, change as you move your cursor from **center** to point **A**?

- Scenario B: Move the cursor **from the circumference** of the ring **to point B**.

  1. (QRB1) What is the **direction** of the force you **feel**, as you move from the **circumference** to point **B**?
  2. (QRB2) How does the **strength** of the force you **feel**, change as you move from the **circumference** to point **B**?

- Compare your experiences in Scenario A with Scenario B.

  1. (QR3) What is the difference in how the forces changed when you move the cursor in the two scenarios?

     Press N on your keyboard. This causes the test charge to become a negative test charge. Repeat what you did in Scenarios A and B. Then answer the questions below:
  2. (QR4) What are the main differences between having **negative** test charge versus having a **positive** test charge?

- Final reflection: Please rate each statement below on the scale provided, by circling your choice

How confident do you feel about the accuracy of the responses have provided for questions on this worksheet?	Highly Confident	Confident	Neutral	Not Confident	Highly Not Confident
I felt that the simulations helped me to respond the questions on this worksheet.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

A.5 Keys for assessments

Table A.1. Key for version 1 of pre-test, post-test, and delayed post-test multiple-choice questions

Question	Answer
1	e
2	d
3	b
4	a
5	b
6	a
7	c
8	a

Table A.2. Key for version 2 of pre-test, post-test, and delayed post-test multiple-choice questions

Question	Answer
1	e
2	d
3	b
4	a
5	b

Table A.3. Key for version 1 of pre-test, post-test, and delayed post-test multiple-choice questions

Question	Answer
1	b
2	b
3	c
4	e
5	b
6	b
7	b
8	c
9	a
10	d

Table A.4. Key for version 1 of pre-test, post-test, and delayed post-test multiple-choice questions

Question	Answer
1	b
2	b
3	c
4	e
5	b
6	b
7	a
8	d
9	a
10	b
11	a

APPENDIX B. BUOYANCY ASSESSMENTS

B.1 Pre-test, mid-test, and post-test

1. Please provide an explanation of why you think some objects float in a liquid, while others sink. You may use diagrams, if you wish. Please try to be as scientific as you can in your explanation.
2. Define buoyant force.
3. The buoyant force on an object is dependent on:
   (a) the object's density
   (b) the mass of the object
   (c) the submerged volume of the object
   (d) the shape of the object
   (*StudyLib*, 2016)
4. The buoyant force on an object submerged in a fluid depends on:
   (a) the object's density
   (b) the fluid's density
   (c) the acceleration due to gravity
   (d) (a) and (b) but not (c)
   (e) (b) and (c) but not (a)
   (*StudyLib*, 2016)
5. The property that most determines whether or not an object will float in oil is the object's:
   (a) Weight
   (b) Mass
   (c) Density

   (d) Volume

   (*StudyLib*, 2016)

6. Does the air exert a buoyant force on my pen if I throw it across the room?

   (a) Yes, why?

   (b) No, why?

   (*StudyLib*, 2016)

7. A balloon filled with hydrogen rises upwards because:

   (a) The pressure inside the balloon is greater than the atmospheric pressure.

   (b) Hydrogen is a gas.

   (c) The weight of balloon is less than the weight of the air displaced by it.

8. An object can float provided its is than the of the fluid

   (a) mass . . .less . . . mass

   (b) density . . . less . . . density

   (c) mass . . .greater . . .density

   (d) density . . . less . . . mass

   (*StudyLib*, 2016)

9. Oil has a smaller density than water. Therefore, an object that will float in oil will:

   (a) float in water, with more of the object submerged

   (b) float in water, with the same amount of the object submerged

   (c) float in water, with less of the object submerged

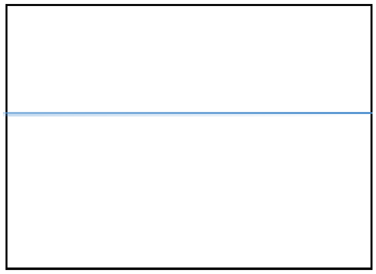
   (d) not float in water

   (*StudyLib*, 2016)

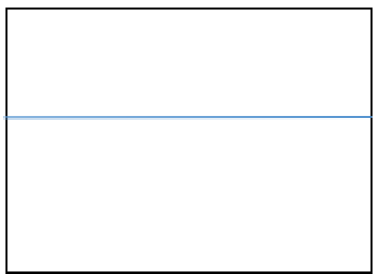
10. A rectangular block is floating in a large pot of pure water. The block is floating with one-half of its volume submerged. Salt is slowly poured into and then dissolved into the water. What, if anything, will happen to the block as the salt is introduced into the water? Why?
    citepstudylib

11. Draw a coin where it would be located:

    (a) In the water if its density was 6.0 g/cm^3.

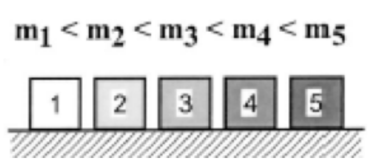


    (b) In the water if its density was 0.8 g/cm^3.

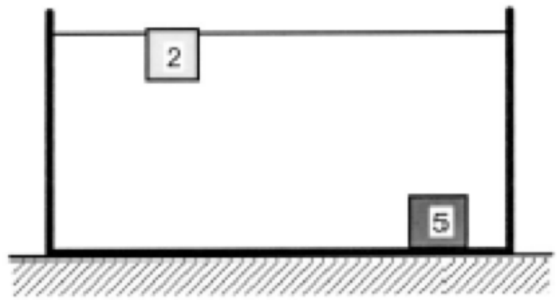


(*Buoyancy Guide*, 2016)

12. Five blocks of the same size and shape but different masses. The blocks are numbered in order of increasing mass (i.e.$m_1 < m_2 < m_3 < m_4 < m_5$):



All the blocks are held approximately halfway down in an aquarium filled with water and then released. The final positions of blocks 2 and 5 are shown. On the diagram, sketch the final positions of blocks 1, 3, and 4. Assume the water incompressible. Explain your reasoning:



(Loverude et al., 2003; Zeineddin & Abd-El-Khalick, 2010)

13. Draw a picture of:

A floating object. Label the forces. Circle the force that is greater.	A neutrally buoyant object. Label the forces. Compare the strength of the forces.	A sinking object. Label the forces. Circle the force that is greater.

<u>B.2 Hands-on Worksheet</u>

Part I. Experiment and Observations:

<u>Test the following different scenarios and record your observations:</u>

1. **Experiment 1**: Partially fill the cup with water and submerge the small potato.

   (a) Write your observations about the level of water before and after you submerge the small potato.

   (b) Try to completely submerge the potato with your finger. What do you feel when trying to submerge the potato in water?

(c) Draw a diagram showing the potato and use arrows the various forces acting on the potato when it is submerged in water. The length of the arrow should represent the strength (i.e. longer the arrow, stronger the force), and the direction of the arrow should represent the direction of the force.

2. **Experiment 2**: Submerge the potato in the corn syrup cup.

   (a) Write your observations about the level of corn syrup before and after you submerge the small potato.

   (b) What do you feel when trying to submerge the potato in corn syrup?

   (c) Do you need more force or less force to submerge the potato in corn syrup versus in water?

   (d) Draw a diagram showing the potato and use arrows (as you did in Experiment 1) to represent the forces acting on the potato.

3. **Experiment 3**: Remove the potato and submerge the smaller rock in the corn syrup.

   (a) How does the force compare with the force needed to submerge the potato in Experiment 1?

   (b) How does the force compare with the force needed to submerge the potato in Experiment 2?

   (c) Draw a diagram showing the potato and use arrows (as you did in Experiment 1) to represent the forces acting on the small rock.

4. **Experiment 4**: Remove the smaller rock and submerge the larger rock into the corn syrup.

   (a) Write your observation about the changes in the liquid level and the force needed to move the object.

   (b) How does the force compare with the force needed to submerge the potato in Experiment 2?

   (c) Draw a diagram showing the potato and use arrows (as you did in Experiment 1) to represent the forces acting on the larger rock.

Part II. Conceptual questions:

1. List all of the factors that influence the buoyant force acting on an object when it is submerged in a fluid and how do each of these factors influence the buoyant force.
2. How do these different factors (identified in question 1 above) interact to make an object float or sink when immersed into liquid?
3. Please provide an explanation of why some objects float when immersed into liquids, while others sink?

B.3 Visuo-haptic Worksheet

Part I. Experiment and Observations:

Test the following different scenarios and record your observations:

1. Experiment 1: Each of the sliders on the computer screen should read 0.1 in the "Play Room" menu.
   (a) Write your observations about the level of water before and after you submerge the object.
   (b) Try to completely submerge the object using the haptic device. What do you feel when trying to submerge the potato in water?
   (c) Draw a diagram showing the object and use arrows the various forces acting on the object when it is submerged in the liquid. The length of the arrow should represent the strength (i.e. longer the arrow, stronger the force), and the direction of the arrow should represent the direction of the force.
2. Experiment 2: Change the density of the liquid to 0.5, while keeping the other.
   (a) Write your observations about the level of fluid before and after you submerge the object.
   (b) What do you feel when trying to submerge the object in the fluid?
   (c) Do you need more force or less force to submerge the object in the fluid compared to Experiment 1?

(d) Draw a diagram showing the object and use arrows (as you did in Experiment 1) to represent the forces acting on the object.

3. Experiment 3: Now keeping other sliders in their current position, change the object density slider to 0.55.

   (a) How does the force compare with the force needed to submerge the object in Experiment 1?

   (b) How does the force compare with the force needed to submerge the object in Experiment 2?

   (c) Draw a diagram showing the object and use arrows (as you did in Experiment 1) to represent the forces acting on the object.

4. Experiment 4: Now, keeping the other sliders in their current position, change the object size slider to 1.0.

   (a) Write your observation about the changes in the liquid level and the force needed to move the object.

   (b) How does the force compare with the force needed to submerge the object in Experiment 2?

   (c) Draw a diagram showing the potato and use arrows (as you did in Experiment 1) to represent the forces acting on the object.

Part II. Conceptual questions:

1. List all of the factors that influence the buoyant force acting on an object when it is submerged in a fluid and how do each of these factors influence the buoyant force.

2. How do these different factors (identified in question 1 above) interact to make an object float or sink when immersed into liquid?

3. Please provide an explanation of why some objects float when immersed into liquids, while others sink?

B.4 Key pre-test, mid-test, and post-test

Table B.1. Key for pre-test, mid-test, and post-test multiple-choice questions

Question	Answer
3	c
4	e
5	c
6	c
7	b
10	c

APPENDIX C. ELECTRICITY AND MAGNETISM RUBRICS

C.1 Pre-test/ post-test/ delayed/post-test

A uniformly positively charged circular ring of radius 1 meter is lying flat on a horizontal table (not shown in figure). The axis of the ring is a vertical line which passes through the center of the ring, extending indefinitely above and below the table. Where should a positive test charge be placed such that it experiences ZERO force due to the charges on the ring?

In the scenario proposed in this open-ended question the participants need to correctly draw the length and the direction of the arrow. For point A the direction is left and the length should be larger than in point E; for point B the direction is down and should be larger than the arrow of the D point; point C has zero force; in point D the direction is left and the length is smaller than in point B; for E the direction is right and the arrow is smaller than E (refer to Figure C.1 for a graphical representation).

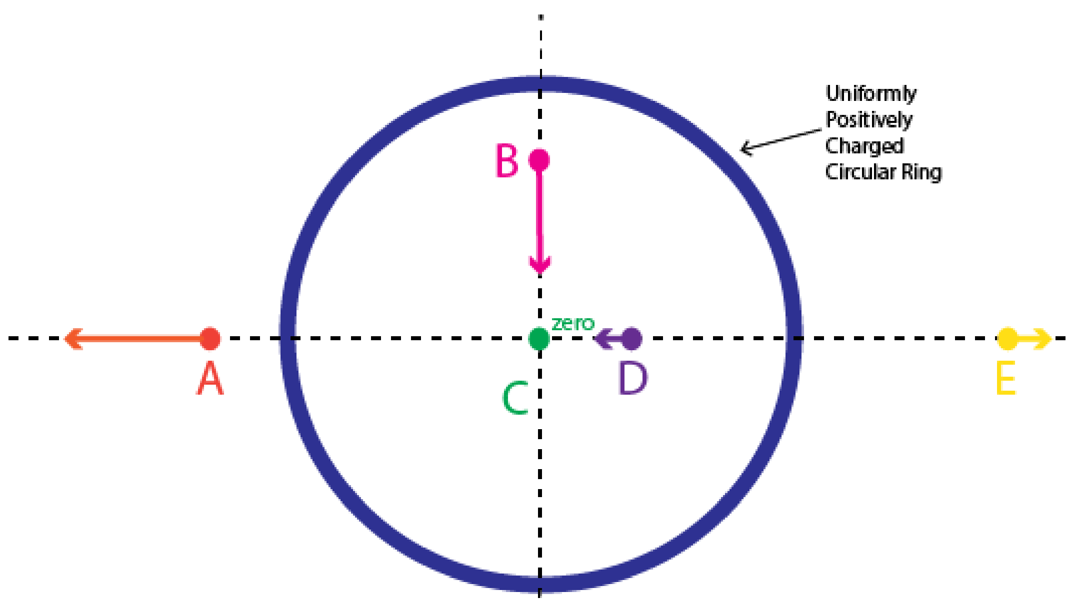


Figure C.1. Correct answers for the uniformly positively charged ring open-ended question

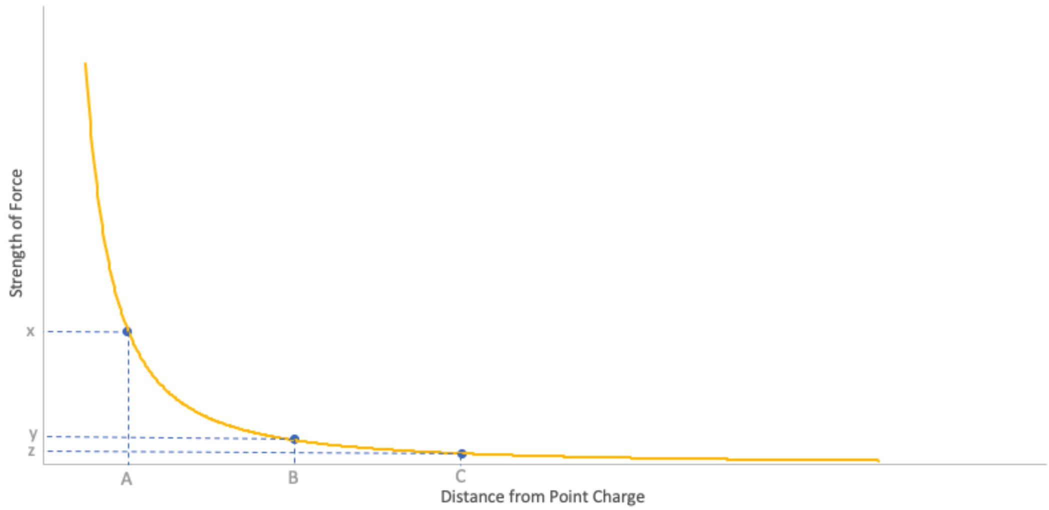
Correct responses were scored with one point and zero points for incorrect responses for the variables length and direction for a total of two per point and 10 per question. Special cases received a score of zero: (a) for direction if arrows are drawn in both directions, (b) if multiple arrows are drawn for the same point, and (c) if the question is totally empty.

C.2 Worksheet

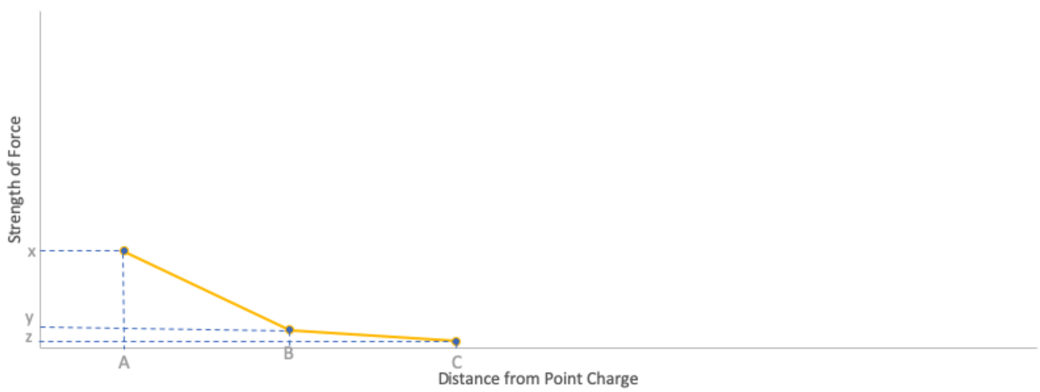
- (Record Table Point) Place the cursor at each point A, then B, then C. At each point, record the information in the table below:

Point	Distance of point from charge (use ruler to measure it)	Direction of the force arrow seen when you when you place your cursor at the point.,(Draw an arrow)	Strength of the force experienced by you when you place your cursor at the point (Read off value from screen)
A	1 unit	$\rightarrow$	x N
B	3 units	$\rightarrow$	y N (less than x/2)
C	5 units	$\rightarrow$	z N (less than y/2)

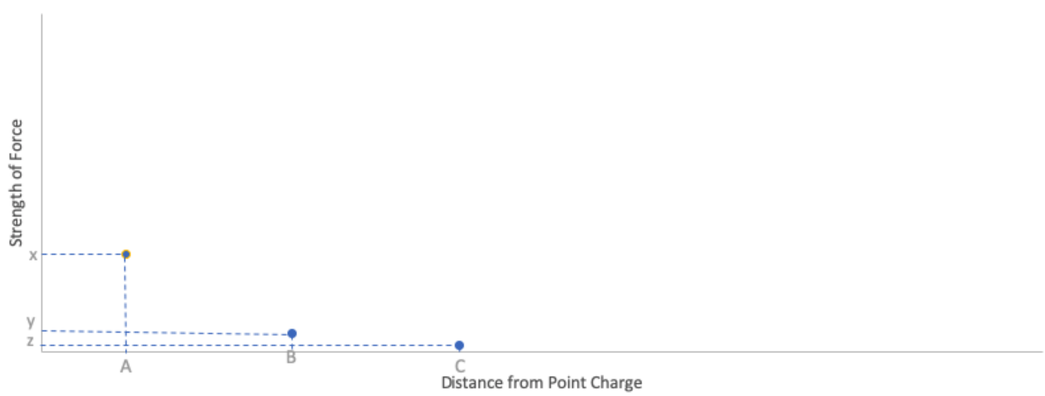
- (QP2) Use the data above to draw a graph of Strength of Force vs. Distance from Point Charge.



(a)



(b)



(c)

Figure C.2. Correct drawings for question QP2 (a) exponential trend line, (b) joint points, and (c) only points.

- Based on the graph, if you double your distance from the point charge, how will the strength of the force change? i.e. will it double, halve, or something else?
  Something else, since the relationship between strength and distance in not linear but exponential decay.

VITA

VITA

- **Education**
  - Ph.D. Technology, Purdue University, West Lafayette, IN May 2020
    Specialization: Computer and Information Technology
    Principal Advisor: Alejandra J. Magana Ph.D.
    Dissertation: Multimodal Virtual Learning Environments: the effects of Visuohaptic Simulations on Conceptual Learning.
  - M.S. Computer and Information Technology, Purdue University, May 2015 West Lafayette, IN
  - B.S. Biotechnology Engineering, Army Polytechnic School, Ecuador October 2011
- Fields of Interest
  Haptic Technology, Virtual Learning Environments, Cyberlearning, Spatial Skills, Technology Innovation, Minorities in STEM.
- Professional Memberships
  - American Society for Engineering Education 2016 present
  - Association for Computing Machinery 2015 - 2016
- Publications
  - Magana, A. J., Serrano, M. I., & Rebello, N. S. (2019). A sequenced multimodal learning approach to support students' development of conceptual learning. *Journal of Computer Assisted Learning*, 35(4), 516-528.
  - Serrano, M. I., Zurn-Birkhimer, S. M., & Baker, R. (2018, April). Non-technical Conferences: Impact on Female Engineering Students. Proceedings of the *Collaborative Network for Engineering and Computing Diversity Conference*, Virginia.

- Zurn-Birkhimer, S., Serrano, M. I., & Baker, R. (2018, June). Impact of Non-technical Conferences in Female Engineering Students Self-esteem and Engineering Self-efficacy. In *2018 American Society for Engineering Education Conference Exposition*, Utah.
- Zurn-Birkhimer, S., Serrano, M. I., Holloway, B.M., & Baker, R. (2018, June). Work in Progress: Online Training in Spatial Reasoning for First-year Female Engineering Students. In *2018 American Society for Engineering Education Conference Exposition*, Utah.
- Serrano Anazco, M. I., Magana, A. J., & Yang, B. (2016, June), Employing Model-Eliciting Activities in Cybersecurity Education. In *2016 American Society for Engineering Education Conference Exposition*, New Orleans, Louisiana. 10.18260/p.26943
- Serrano, M. I., & Groh, J. L. (2016, October). Travel grants which facilitate engineering leadership identity in female engineering students. In *2016 IEEE Frontiers in Education Conference* (pp. 1-4).
- Harriger, A., & Serrano, M. (2014). Scratch for Arduino: Exergaming Development. In *IAJC/ISAM Joint International Conference* (pp. 1-7).
- Harriger, A., & Serrano, M. (2014). Using flowchart programming to create exergames. In *IAJC/ISAM Joint International Conference* (pp. 1-10).
- Mendez, D., & Serrano, M. (2013, March). Using Twitter to Engage Ecuadorian High School Students in STEM. In *Society for Information Technology Teacher Education International Conference* (Vol. 2013, No. 1, pp. 3522-3529).

• Fellowships and Awards

- Poster session of the Purdue Polytechnic Future Work and Learning Research Impact Area, 3rd place, 2019
- Susan Bulkeley Butler Center for Leadership Excellence fellow, “ Understanding Spatial Reasoning of Women in Engineering, 2017

- Research Projects
  - Understanding Spatial Reasoning of Women in Engineering, Susan Bulkeley Butler Center for Leadership Excellence Fellowship.
    Research Assistant, May 2017 May 2018
    * Developed and implemented spatial skills workshops used for training first year female engineering students.
    * Designed experiment to understand impact of the spatial skills workshops.
  - Travel Award, Woman in Engineering Program (WIEP) at Purdue University.
    Research Assistant, 2015 2017
    * Designed experiment to assess impact of awards.
    * Familiarized with numerous conferences that provided academic and work development for women in STEM.
  - Teaching Engineering Concepts to Harness Future Innovators and Technologists (TECHFIT), NSF-ITEST funded project.
    Research Assistant, January 2014 May 2015
    * Co-authored several tutorial guides for the project which were used as a reference for middle school teachers and students.
    * Developed and implemented several fitness devices using Phoenix Contacts nanoNavigator software and hardware to encourage physical activities and scientific curiosity in middle school children.
    * Acquired programming /scripting skills in Perl, flowchart programming, Scratch, and Scratch for Arduino to develop tools for data collection, data mining, and physical computing activities.
  - Surprising Possibilities Imagined and Realized through Information Technology (SPIRIT), NSF supported project. Research Assistant, August - December 2013
    * Learned numerous outreach techniques focus on STEM fields to inspire youngsters to pursue advanced degrees in Information Technology fields.
    * Generated and managed a chronological archive of SPIRIT files improving information retrieval.

* Created a contact database of SPIRIT participants to facilitate future research and tracking.