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Investigating the Impact of Visuohaptic Simulations for the Conceptual Understanding of Electric Field for Distributed Charges

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INVESTIGATING THE IMPACT OF VISUOHAPTIC SIMULATIONS FOR THE CONCEPTUAL UNDERSTANDING OF ELECTRIC FIELD FOR DISTRIBUTED CHARGES

A Thesis

Submitted to the Faculty

of

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by

Uzma Abdul Sattar Shaikh

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This thesis is dedicated to my husband, Sikandar Mashayak. His love and encouragement ignited within me the passion to achieve and learn more.

This thesis is also a dedication to my parents, Abdul and Mohammadi. Words fall short to convey my immense gratitude to them for the numerous sacrifices they have made to put my good before their own individual aspirations.

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TABLE OF CONTENTS

Page

Page

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

LIST OF ABBREVIATIONS

E&M – Electricity and Magnetism

CATLM – Cognitive Affective Theory for Learning with Media

GLOSSARY

Computer simulation: "Computer simulations are programs that contain a model of a system (natural or artificial, e.g., equipment), or a process" (Jong & Joolingen, 1998).

Discovery learning: The idea of constructivism suggests that students learn better when they construct knowledge by themselves. The self-learning approach is better than the knowledge simply demonstrated or shown to them by a teacher (Loveless, 1998, p. 285).

Cognitive Load Theory: Cognitive load theory suggests that there is a limited working memory. If a learner is given excessive information and the complexity of the associated instructional materials is not handled well, it may lead to cognitive overload. The problem of cognitive overload can hamper the learning process. (Sweller, 1988)

Guided Inquiry learning: "Inquiry that is guided by an instructional team to enable students to gain a depth of understanding and a personal perspective through a wide range of sources of information is called Guided Inquiry" (Kuhlthau, Maniotes & Caspari, 2007).

ABSTRACT

Shaikh, Uzma Abdul Sattar. M.S., Purdue University, December 2015. Investigating the impact of visuohaptic simulations for the conceptual understanding of electric fields for distributed charges. Major Professor: Alejandra Magana.

The present study assessed the benefits of a multisensory intervention on the conceptual understanding of electric field for distributed charges in engineering and technology undergraduate students. A novel visuohaptic intervention was proposed, which focused on exploring the forces around the different electric field configurations for distributed charges namely point, infinitely long line and uniformly charged ring. The before and after effects of the visuohaptic intervention are compared, wherein the intervention includes instructional scaffolding. Three single-group studies were conducted to investigate the effect among three different populations: (a) Undergraduate engineering students, (b) Undergraduate technology students and (c) Undergraduate engineering technology students from a different demographic setting. The findings from the three studies suggests that the haptic modality intervention provides beneficial effects by allowing students to improve their conceptual understanding of electric field for distributed charges, although students from groups (b) and (c) showed a statistically significant increase in the conceptual understanding. The findings also indicate a positive learning perception among all the three groups.

CHAPTER 1. INTRODUCTION

1.1 Introduction

This chapter provides an introduction to the research study. The chapter describes the scope, significance and the gaps addressed by the current research work. It also defines the limitations and assumptions associated with the research.

1.2 Statement of Purpose

Many students do not have a strong understanding of the foundational concepts of electric fields, field lines, field intensity and electric force. Previous research studies suggests that the immature understanding of the fundamental concepts in physics affects the understanding of advanced concepts and laws of physics (Maloney et al., 2001). The phenomena of electric field configurations is an invisible phenomena and students often find it difficult to understand the concepts of electric fields for different configurations. Maloney (2001), Galili (1995) and Raduta (2005) in their research they have found that the theoretical concepts like electricity and magnetism are not wholly understood by students and there are misconceptions associated with the fundamental understanding of these basic concepts. In their research work, they have all developed some assessment instruments and provided some base-line performance data with a hope to inspire others to develop new and improved ways to teach electricity and magnetism.

With technology growing at an unimaginable pace, haptic technology has emerged making it possible to explore the sense of touch in the virtual world of computers. However, the use of haptic technology remains largely unexplored in the field of educational research. Morris et al. (2007) explored the use of force feedback to teach a specific mechanical skill that requires remembering a series of one-dimensional forces using three different approaches namely haptic only, visual only, or combined visuohaptic training. The findings from this research indicate that the outcome from the visuohaptic training resulted in a significantly accurate recall as compared to the visual only or haptic only. Also, the haptic only approach of training was less effective as compared to the visual only training. Sanchez (2013) investigated the efficacy of using visual only and visuohaptic simulations for improving the learners' understanding of electromagnetic concepts. The findings of this research indicate no significant difference in the two treatment groups.

In the experimental design of the research done by Sanchez (2013), the visual and visuohaptic simulation served as a free exploration tool where the student did not work on any predefined test scenarios. This may have been one of the reasons that the study did not yield any significant results between the two treatment groups. In the current experimental study, a refinement was added to this design by adding a guided inquiry approach where the learners were required to work on predefined test scenarios.

1.3 Significance

Haptics comes from the Greek word "haptein" (meaning "to hold"). Haptic devices have become more affordable over the last decade or so and researchers have attempted to develop relevant learning modules to help students connect science, technology, engineering, and math (STEM) concepts with the actual physical phenomena (Richard, Okamura, & Cutkosky, 1997). The technology is gaining momentum especially in the field of medical simulations. Minogue and Jones (2009) point out that fewer studies have been done in the field of haptic technology for educational research. Some previous research exploring conceptual understanding has not reported any promising results to provide any concrete evidence to strongly infer that there is any cognitive gain because of using the haptic technology. Electric fields for distributed charges is a fundamental concept in physics. Electric fields and associated topics involves associating the concept of electric fields and force feedback. Haptic technology can be used to represent the concepts of electric fields and help students understand the concept of electric fields and field lines. There is very less research done in the field of haptic technology being useful for education. This would be important to provide concrete evidence that the use of haptics technology in learning creates a cognitive impact.

1.4 Scope

The scope of the research includes developing visuohaptic simulation for electric fields for distributed charges and using these simulations in an educational setting to investigate their efficacy in learning the concepts of electric field for distributed charges. In the current study, the researcher will focus on understanding if using a visuohaptic simulation would help a student garner an improved conceptual understanding of electric fields for distributed charges. Distributed charges imply a group of charges bound together. The study uses the principle of scientific discovery learning. In scientific discovery learning, the emphasis is on combining simulations with instructional support to increase the effectiveness and efficiency of discovery learning. The simulation for the different electric field configurations would serve as a conceptual model for the learner. A learner using the simulation would basically alter certain input variables and notice the changes in values of certain output variables. In this case, the learner changes the distance by moving the cursor (input variable) and observes how it changes the value of the force or electric field (output variable) and the direction of the electric field (output variable).

Pretest and posttest assessments were prepared with the help of subject matter experts in physics education. Physics text books and online resources were used to extract questions. Comparing the efficacy of before and after effects of using visuohaptic simulation was a key component of this research. The assessment was designed to focus only on gauging the conceptual understanding of students and not the learners' ability to solve calculation based questions concerning electric fields.

1.5 Research Questions

The present experimental study focused on probing the efficacy of visual simulations combined with force feedback using haptic technology, specifically targeted to the conceptual understanding of electric fields for distributed charges. Three single-group studies were conducted to investigate the effect among three different populations: (a) Undergraduate engineering students, (b) Undergraduate technology students and (c) Undergraduate engineering technology students from a different demographic setting.

The research questions which guided the study are:

1. Can engineering, technology and engineering technology undergraduate students (with varying physics backgrounds) improve their conceptual understanding about electric fields for distributed charges after being introduced to visuohaptic simulations?
2. What are the students learning perceptions after using the visuohaptic simulations to learn the concepts of electric fields for distributed charges?

1.6 Assumptions

The assumptions associated with the research:

1. All the students from a learning group have a similar level of understanding of the concepts of electric fields.
2. The students participating in the studies have some very basic knowledge about electric fields and the concept of positive and negative charges.
3. Since the study was conducted outside the setting of a regular course, students participating in the studies put in their best efforts even though their performance in this test did not contribute to their grades.

1.7 Limitations

The current research had some limitations, which are listed below.

1. The haptic device used for the study was the Novint Falcon. The main reason to use the Falcon versus other haptic devices like the Phantom is its affordability in terms of cost.

2. Since the study was conducted in a lab setting, there was just one hour or a half hour conducted to teach students about how to learn with touch. This may have not be enough time for students to explore the haptic device.
3. The maximum time allotted for the study was a maximum of two lab sessions.
4. Students completed the experiment during their assigned laboratory session.

1.8 Delimitations

The delimitations for the current research work are as follows:

1. Participants who did not complete all the components of the assessment were disregarded during the process of data analysis.
2. The study was performed using a set of simulations which will explore the point charge, ring charge and line charge.
3. The study does not focus on the mathematical derivations for the distributed charges for electric fields.
4. The aim of the study is to focus less on the calculation based assessment and more on the conceptual based assessment.
5. Even though a qualitative study would be an interesting option to evaluate the learners' conceptual understanding, this study is purely quantitative in nature. The assessment contains questions which be designed to judge the conceptual understanding of the learner.

1.9 Chapter Summary

This chapter explains the purpose for conducting this research study. It explains the scope of the study and the contribution that the study could make to the field.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The chapter of literature review addresses preceding work related to the complications students face when understanding unobservable and abstract concepts, especially related to conceptual understanding of electric fields. The use of visuohaptic simulations for teaching and learning will be explained in the following section. The last section would elaborate on the guiding theory for the experimental work, which is scientific discovery learning. The mapping of the elements of scientific discovery learning to the current research activities will also be discussed.

2.2 Problems in Conceptual Understanding of Physics

Many of the phenomena in theoretical physics are macroscopic/invisible making it extremely difficult for students to develop a solid understanding of the relevant fundamental concepts. Many instructors who teach physics courses feel that the process of problem-solving has the potential to both help students learn physics concepts as well as well as a reliable way for instructors to validate that understanding for assessment purposes (Maloney, 1994). Unfortunately, sometimes students are not able to wholly understand or describe the meaning of their own algebraic equations or methods that they use to propose solutions to problems (McDermott, 1991). McDermott (1991) reasoned that correctly calculating mathematical components does not necessarily establish that a comparable level of conceptual understanding is achieved. Kim and Pak (2002), in their research work investigated the relation between solving physics problems from textbooks and conceptual understanding. The findings of the study suggest that there was no relation between the number of problems a student solves and the conceptual understanding of the students, indicating the process of solving problems has less impact on conceptual understanding. Sometimes, instruction tends to focuses more on the process of solving problems and places less emphasis on achieving intellectual goals. This could sometimes mislead students to focus on more on the algorithmic aspects than the conceptual aspects of physics.

2.3 Problems in Conceptual Understanding of Electric Fields

Authors of “Brief Electricity and Magnetism Assessment (BEMA)” , Chabay and Sherwood (2006), suggest that it is crucial for students to have a strong understanding of electricity and magnetism concepts since these concepts are the foundations to advanced concepts. The concepts are also the basis to many current and novel technologies. From the perspective of an instructor, teaching such unobservable and abstract phenomena in an effective and comprehensible format is a formidable task. Bagno and Eylon (1997) conducted research on students in a high school E&M course and the findings from the study suggest that students are deficient in grasping central ideas associated with the E&M concepts, conceptual understanding and gauging the relationship between concepts to solve problems.

Students find it difficult to understand concepts of electromagnetic induction and electric potential (Dega, Kriek, & Mogese, 2013). E&M concepts are complex, invisible and hence the fundaments are difficult for students to understand the associated abstract relations (Chabay & Sherwood, 2005). The students do not see or feel these concepts and face issues when they try to apply various physics laws to problems associated with E&M. Research shows that there is a glitch in students understanding about fields and field line concepts and the inability to distinguish between them due to a lack of graphical representation (Tornkvist et al., 1993). The increased number of topics to be covered in a short period of time leads to a rapid introduction of many fundamental E&M concepts to students, which can prove to be extremely overwhelming to them (Chabay & Sherwood, 2006). Some research explains that there is a mismatch of knowledge of physics and how it is applied in E&M scenarios leading to misconceptions and complexities in students' conceptual understanding (Galili, 1995).

Previous research has indicated that the students' knowledge about E&M concepts is not very thorough. Conceptual Survey in Electricity and Magnetism (CSEM) was designed by authors Maloney et al. (2001) to gauge students' familiarity about E&M concepts. Comparing the transition from pretest to posttest on applying the test to more than 5000 students indicated that students' face a lot of difficulties in understanding these concepts. CUE (Colorado Upper-Division Electrostatics) is a similar assessment instrument containing 17 conceptual questions, where 15 questions deal with electrostatics and 2 questions are based on magnetostatics. CUE was designed to evaluate how a student approaches a problem, justifies the approach used and explain it with the underlying math and physics (Chasteen & Pollock, 2009). The results for this research suggested that students in research-based interactive courses outperformed the students who were in a traditional lecture-taught courses.

The traditional classroom approach for teaching E&M concepts alone is not beneficial for a strong fundamental understanding (Dega et al., 2013). Chabay and Sherwood (2006) described that E&M concepts are taught with the method which focuses more on solving the mathematical problems using equations than spending time on explaining the core fundamental concepts. Students often are overwhelmed with coursework, making it difficult for them to take the time to garner a deep understanding of these fundamental concepts.

2.4 Simulations in Educational Research

Students often encounter challenges when they attempt to conceptualize different science concepts or phenomena. Simulations bring a component of realism in the form of visualizations to otherwise invisible concepts or theories. Both physical and virtual experiments are designed with an intent to achieve some learning goals, but virtual experiments enable to sometimes experiment those scenarios which are not possible in a physical experiments. Also, virtual experiments enable learners to conduct many tasks in a short amount of time (de Jong, Linn, & Zacharia, 2013). The results from the study by researchers Triona and Klahr (2003) suggests that the use of both physical and virtual materials have equivalents results for a similar learning scenario. Other investigations have reported less impressive results about using computer simulations for teaching science concepts. Some of them found no advantage in using computer simulations over traditional methods (Winn et.al, 2006). Even when the gains made by students were shown by using computer simulations, some argue that the gain should be attributed to effective teaching methods and effects of teachers (Clark, 1994).

Some other studies indicate that computer simulations have been an asset for student learning. Chang et al. (2008) used a physics simulations of an optical lens for high school students and compared students learning about basic characteristics of the lens from the traditional laboratory group and the simulation group. The students from the simulation group outperformed students from the laboratory group. Electricity and magnetism concepts, which are very complex and otherwise invisible can be represented using effective computer simulations (Dega et al., 2013). Jimoyiannis & Komis (2001) compared the fundamental understanding gained by two groups of students about the physics concepts of acceleration and velocity. Both the control and experimental groups attended a lecture, whereas the experimental group additionally worked on computer simulations. The experimental group showed significantly higher gains.

2.5 Haptic Technology

Technology has been growing very rapidly and so is the integration of technology with education. Haptic technology enables a user to feel the different aspects of touch like vibrations, forces and motions. The technology allows a user to virtually feel and manipulate objects on a computer screen. Imagine pushing a ball on the screen or feeling the texture or surface of an object. It is analogous to computer graphics in terms of functionality. Haptics simulates the sense of touch just like computer graphics simulates visualization. The use of this technology in video games is very popular and the Novint Falcon is specifically designed to target the audiences who play 3D games. However, the use of haptic technology in the field of education remains largely unexplored. Revesz came up with the word “haptics” in the year 1931. The word “haptics” derives its origins from the Greek words “haptein” which means “to hold” (Révész, 1950).

The sense of touch is a powerful sense that we are born with. Unlike the other four primary senses, which are consolidated at specific parts of the body, the sense of touch is distributed all over our body. Haptics enables the sense of touch in a virtual world and the different sensations like hardness, shape, weight and texture of virtual objects in computer simulations (McLaughlin, Hespanha, Sukhatme, 2002). A greater sense of immersion in the learning environment happens when one is able to feel, touch and manipulate objects versus only seeing or listening (Srinivasan, 1995). Visualization remains a primary mode of interaction in the virtual world of computers, even though touch is the most common way people use to interact with the physical objects (Thurfjell et al., 2002).

2.6 Haptic Technology in Educational Research

Haptic technology is gaining momentum in the field of training using computer simulations (Minogue et al., 2006). By integrating haptic technology with computers, instructors can create virtual laboratories where students can have a hands-on learning experience. Students can use these virtual simulations to simulate the work they can perform in physical laboratories and explore various phenomena (Dalgarno et al., 2003).

The current applications of haptic technology can be seen in the field of geoscience, medical science, 3D modeling, entertainment and mechanical simulations (Pantelios et al., 2004).

Educators believe that hands-on activities are influential learning tools that can improve student learning and performance (Minogue & Jones, 2006). Haptic devices as learning tools can facilitate hands-on experiences. Research has proven that for students it is more effective to learn abstract concepts when there is “touch” or manipulation of objects than when there is only visual support (Jones & Vesilind, 1996).

The true potential of haptic technology in education field has not been fully harnessed and very less research has been done to investigate the effectiveness of haptics in education (Minogue & Jones, 2009). Electric fields and distributed charges been a topic that has received little attention in regards to the implementation of haptic technologies. Sanchez (2013) has investigated the efficacy of using visual only and visuohaptic simulations for improving the learners’ understanding of electromagnetic concepts. The findings of this research indicate no significant difference in the two treatment groups.

Some previous research exploring conceptual understanding has not reported any promising results to provide firsthand evidence for the existence of the cognitive impact of haptic technology (Sanchez, 2013). For understanding simple concepts, sometimes only the visual simulations suffice and there is no need to add the haptic component to the simulations. In the current experimental study, the research focuses on more difficult concepts which are invisible. In the experimental design of the research done by Sanchez (2013), the visual and visuohaptic simulation served as an exploration tool where the student did not work on any predefined test scenarios. This may be one of the reasons that the study did not yield any significant results between the two treatment groups. In the current experimental study, the current research work intends to add a refinement to this design by adding a guided inquiry approach where the learners would be working on predefined test scenarios. The current research also embodies the principle of scientific discovery learning to provide the necessary scaffolding to guide the simulations in our research work.

In spite of the recent technological advances, the use of haptics in the field of education remains largely unexplored. The reason for this subdued use is the cost associated with developing the technology as well as the challenges associated with the level of realism provided by the current haptic devices. In spite of these challenges, the potential that haptics can bring in future is something to watch out for. Just as all the trends in other technologies, the haptic technology is becoming cheaper and the various applications are moving towards bringing more realism in its use. Haptics in the future can prove to be a revolution in the way we interact with computers and the virtual world. More research is needed in the field of using haptics technology for educational research. This would be important to provide concrete evidence that the use of haptics technology in learning creates a cognitive impact.

CHAPTER 3. THEORETICAL FRAMEWORK

3.1 Interactive Multimodal Learning Environments

The theoretical framework which guides the current experimental design is based on research done by Moreno & Mayer (2007) which focused on the principles dealing with interactive multimodal learning environments. The basic idea proposed by the framework is that effective learning occurs when there is a clear integration of prior knowledge with new knowledge leading to coherently structured form of knowledge.

Moreno and Mayer's (2007) *cognitive-affective theory of learning with media* (CATLM) points out four crucial principles of learning with multimodal learning environments. Figure 3-1 shows a model of CATLM. As shown in Figure 3-1, there is a separate processing modality for different instructional media. The working memory has limited processing capacity for each of the different modalities. For learning to be effective, any new information needs to be appropriately selected, organized and integrated with existing knowledge. Motivation is a crucial factor when the learner engages in a multimodal environment. They also suggested that at a given time only a limited number of elements can be processed by the working memory. Learners can possibly learn more effectively when they are not required to process excessive information corresponding to one modality only. Wong et al. (2009) suggests that when there is more strain on one of the processing modalities while interacting with a multimedia environment it could lead to a potential cognitive overload.

The study by researchers Mayer and Moreno (2002) suggests that when a learner is exposed to a lot of visual information it can overload the visual working memory of the learner. Austin (2009) points out that such a cognitive overload limits the resources available to make connections between information from different channels. Learrning can be more effective and have a deep-seated influence, if learners are not overload with excessive information from a specific sensory channel. Figure 3-1 describes the components of the framework for CATLM.

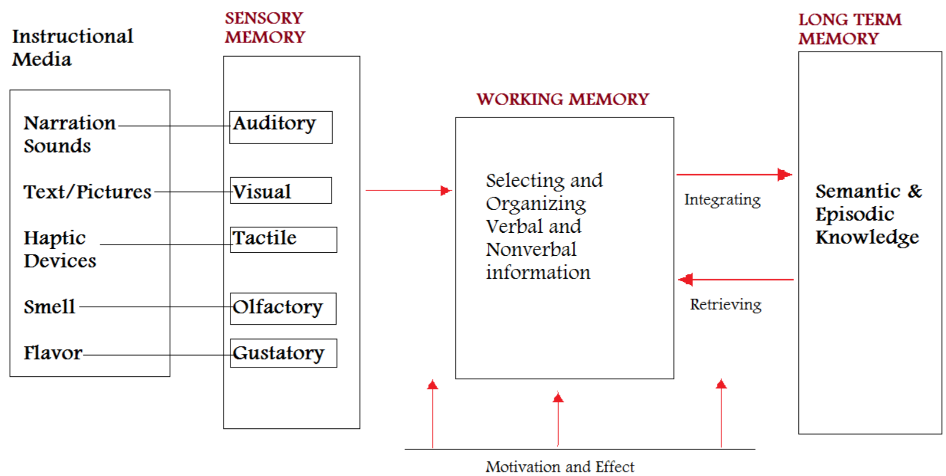


Figure 3-1. Framework showing *Cognitive Affective Theory of Learning with Media*

3.2 Implications of the Theoretical Framework for Study Design

The implications of the theoretical framework for the design of the study relate to the integration of the five design principles proposed by CATLM. These five principles were adapted to our study as depicted on Table 3-1.

Table 3-1. Using the principles of CATLM in the experimental design.

Design Principles and Corresponding Theoretical Rationale (Moreno and Mayer, 2007)			Adaptation of Principles for the Study
Guided Activity	Students learn better when allowed to interact with a pedagogical agent who helps guide their cognitive processing	Guided activity encourages essential and generative processing by prompting students to engage in the selection, organization, and integration of new information	The experimental design is a guided activity with the instructional module serving like a guide to the learner.
Reflection	Students learn better when asked to reflect upon correct answers during the process of meaning making	Reflection promotes essential and generative processing by encouraging more active organization and integration of new information	The students complete the lab reports and record their observations and reasoning behind choosing the correct answer.
Feedback	Students learn better with explanatory rather than corrective feedback alone	Explanatory feedback reduces extraneous processing by providing students with proper schemas to repair their misconceptions	The students were given a correct explanatory feedback for questions in the instructional module.
Pacing	Students learn better when allowed to control the pace of presentation of the instructional materials	Pace control reduces representational holding by allowing students to process smaller chunks of information in working memory	The experimental study was designed so that students can control the pace of their work and learning.
Pre-training	Students learn better when they receive focused pre-training that provides or activates relevant prior knowledge	Pre-training helps guide the learner's generative processing by showing which aspects of prior knowledge to integrate with incoming information	In order to element the "wow" effect of the haptic technology, the students were exposed to a haptics pre-training session.

3.3 Pedagogical Approach for the Design of the Learning Task

Scientific discovery learning was the pedagogical approach that guided and supported the learning task. Jong & Joolingen (1998) proposed the approach of scientific discovery learning, which can be perceived as a learning model in which a computer model in the form of a simulation is used to represent a concept or phenomena. The learner uses this simulation and infers the fundamentals of the concept or phenomena through an experimentation process. The process is a form of discovery learning, which is centered on the concept of self-learning. Additionally, it suggests that when you combine simulations with some instructional scaffolding it makes the learning process more effective and efficient. Embedding instructions in the simulations enables to overcome the problems associated with discovery learning.

The simulation for the different electric field configurations in the current experimental work would serve as a conceptual model for the learner. Learner's basic action would be to change certain input parameters and observe the resulting changes in values of output parameters. In this case, the learner would change the distance by moving the cursor (input variable) and would observe how it changes the value of the force or electric field (output variable) and the direction of the electric field (output variable). Scientific Discovery Learning suggests some mechanisms to assist learners in the discovery process, which are further elaborated in the section below.

3.3.1 Direct access to Domain Knowledge

Learners need to have some domain knowledge which serves like a prerequisite for any experimental study. The time of availability of domain knowledge plays a crucial role in the effectiveness of the learning process. The research by Berry and Broadbent (1987) suggests that it is important to provide information needed by the learner at the appropriate time while using the simulation to make the learning more effective. They suggest that this approach is better than providing the required information before the learner uses the simulation. In the case of our experimental study, the learners were provided with a prerequisite information in the form of a knowledge section in the lab report to refresh the basic concepts of electric field.

3.3.2 Model Progression

The principle of model progression suggests that it might be difficult for a learner to comprehend all the aspects of a simulations all at once. The process of model progression is an incremental process which involves learning from basic aspects and then gradually moving ahead to learn more complex aspects of a simulation. In our experimental study, the learner starts with the basic point charge simulation and then explores the infinitely long line charge, and uniformly charged ring in the increasing order of complexity.

3.3.3 Support for the Design of Experiments

To support a learner in designing experiments the learning environment can provide experimentation hints. In the experimental study done by Rivers and Vockell (1987) hints like "it is wise to vary only one variable at a time" were given to the learners. These hints assisted the students while they worked with the computer simulations. These forms of additional hints did not affect the learning outcome, but only supplemented the students' experimentation abilities. The simulations for all the three studies was supplemented with hints for each configuration.

3.3.4 Planning Support

The process of planning support assists the learner in the learning process. Showalter (1970) suggests that using an inquisitive process with questions can be used to guide the learner through the learning process. Specific questions were asked to the learner in order to get the learners attention focused on the crucial components of the simulations. The instructional module in the experimental study was supplemented with questions as the learner's progress through the sections of the different configurations. The question were framed like "What is the force you feel at the center of the configuration?", "Do you feel the force decreasing as you move away from the center?" , "At which point do you feel the maximum force?"

3.3.5 Structuring the Discovery Process

Linn and Songer (1991) investigated the impact of providing students with a sequence of experimentation steps like the activities to do prior to, during and post the experiment and found that providing explicit details about each individual step was effective. The learning activities in the experimental study were structured to have the following learning tasks:

- Pretest – an assessment to check the initial understanding about electric field concepts.
- Introduction of the haptic technology and its applications.

- Familiarization with the Novint Falcon device, where students are exposed to sample visuohaptic simulations.
- A hands-on with the buoyancy simulation with as associated guided learning task.
- The instructional module designed with a step by step approach for the different configurations and supporting questions and hints for the simulations.
- Posttest - an assessment to check the understanding about electric field concepts after the visuohaptic intervention.

CHAPTER 4. METHODOLOGY

The objective of the current research was to examine the efficacy of using visuohaptic simulation for the conceptual understanding of electric fields for distributed charges. The four important aspects highlighted in this chapter are: (1) to describe the research design, (2) to describe the learning context, (3) to list out the detailed procedures and the design of the data collection instrument and (4) to describe the statistical procedures used for analyzing the data.

4.1 Research Design

The pretest posttest single-group design was developed to investigate the impact of visuohaptic simulations for the conceptual understanding of electric field for distributed charges. Because of the exploratory nature of this research design, no control group was included. The study had a formative nature and therefore three iterations of a single group pre and posttest assessment was implemented along with a survey to collect information about participants' experience. Figure 4-1 describes the research design.

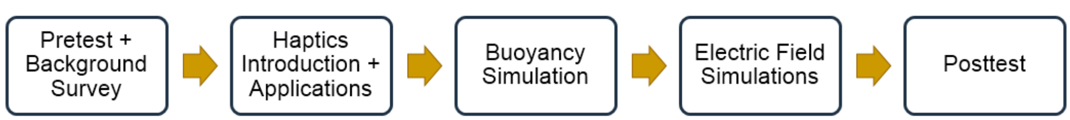


Figure 4-1. Research Design showing the different phases

4.2 Participants and Context

The research was conducted in the form of three different studies. For the purpose of simplicity of reference, the three studies will be referred to as Study One, Study Two and Study Three. The main difference between these three studies were the target population and participants' background preparation. The participants for Study One were nineteen undergraduate engineering students from a Midwestern university in USA. Study Two participants consisted of thirty undergraduate students from the Purdue Polytechnic Institute (originally referred to as the School of Technology), while Study Three participants comprised of twelve undergraduate engineering technology students from a university in Peru. All the three studies will be described in detail in the consecutive chapters.

4.3 Materials

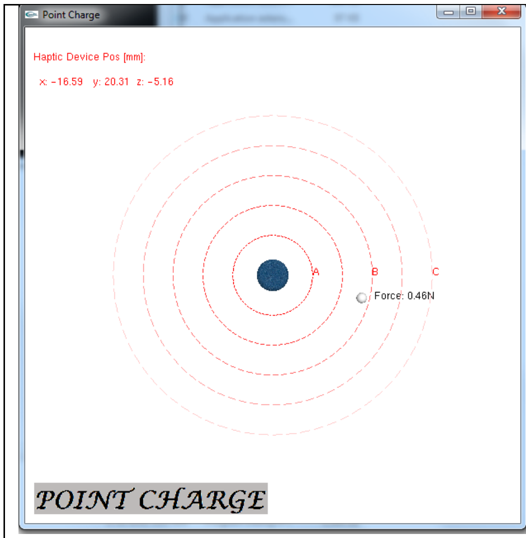
The learning materials included three simulations namely point charge, infinitely long line charge and uniformly charged ring, a lab report to facilitate a guided learning experience and a Novint Falcon device (see Figure 4-2). Haptic sensing consists of two types which are tactile and kinesthetic. Tactile sense is the responsiveness of stimulation to the outer surface of the body, i.e., the skin. Kinesthetic sense implies the responsiveness to limb positions and muscle tensions. Haptic displays can be categorized roughly by the main receptor groups that they engage. Tactile displays stimulate the skin and the most popular and well-known tactile display is vibrotactile – vibrations delivered to the skin surface via resonant-type vibrators, piezoelectric actuators, etc. Kinesthetic displays are usually force-feedback devices and they provide information to various body sites through force. A common type of consumer-grade kinesthetic display is force-feedback joystick. While vibrotactile displays deliver stimulation that is abstract but very useful for notification and alert, force-feedback devices are more intuitive to the user as we naturally understand, for example, that a large resistance force implies a surface that cannot be penetrated. To understand the operation of a typical force-feedback device, imagine holding onto the handle of a small robot. As the user moves the handle in the three-dimensional (3D) space, the location of the handle tip is tracked by the robot and can be used as the current location of, say, a positive electrical charge, controlled by the user. Now assume that the positive charge is being moved by the user in an electrical field formed by electrical charges in the vicinity, then the force exerted on the positive charge by the electrical field can be calculated, scaled, and then sent to the handle of the robot. As the user counter-balances the robot handle with his/her hand, the user experiences the force and its variations due to the positive charge moving around in the electrical field. The haptic experience can be coupled with a real-time visual animation of the positive charge being manipulated and the collection of electrical charges and the resulting electric field (field lines). This enables the user to experience what it’s like to be the positive charge in the electrical field and how its movements interact with a static electric field.

Figure 4-2. Novint Falcon

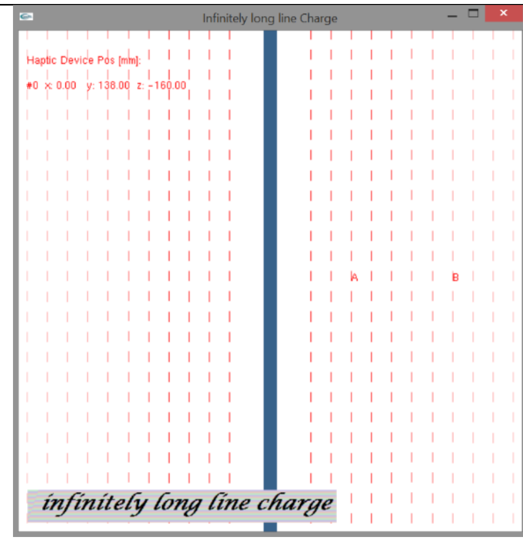
For educational purposes, force-feedback devices are preferred for visuohaptic rendering of physical phenomena that are otherwise "invisible," including electromagnetism, buoyancy and atomic force microscopy. Devices with end-effectors that can be moved in 3D allow the simulation of forces in response to an object being manipulated in a virtual environment. In addition, cost is also an important consideration since we need at least a dozen or so haptic displays in a laboratory setting in order to allow a classful of students to simultaneously engage in learning activities in a group setting. Premium devices such as the PHANToM and the Omega have relatively large workspace, force range and bandwidth (i.e., more responsive), as well as higher cost. As far as we are aware, the Falcon is perhaps the only cost-effective force-feedback device due to its reasonable force range and workspace, and affordability. Table 4-1 describes the specifications of the Novint Falcon.

Table 4-1. Specifications of Novint Falcon (Extracted from www.novint.com)

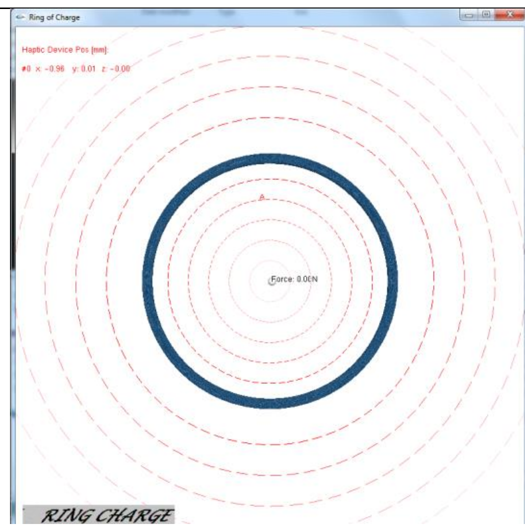
Feature	Specification
3D Touch Workspace	4" x 4" .x 4"
Force Capabilities	Greater than 2 lbs
Position Resolution	Greater than 400dpi
Quick Disconnect Handle	Less than 1 second time change
Communication Interface	USB 2.0
Size	9" x 9" x 9"
Weight	6 lbs
Power	30 watts, 100V-240V,50Hz 60Hz
Device Input	30V DC, 1.0A



(a) Point charge scenario



(b) Line charge scenario



(c) Ring charge scenario

Figure 4-3. Screenshot of visuohaptic simulations – (a) Point Charge, (b) Line Charge (c) Ring charge

The visuohaptic simulations have been developed using an open-source framework called Chai 3D. It is an open source framework built using C++ and OpenGL. It supports various compilers on various operating systems. It can be used as a low level API to talk to devices as well as a high level API with visual and haptic rendering support. Figure 4-3 shows the three visuohaptic simulations for point charge, infinitely long line charge and ring charge.

4.4 Learning Design guided by the Cognitive-Affective Theory for Learning with Media

The guided laboratory report was the main vehicle to scaffold the learning experience implementing principles such as guided activity, reflection, feedback from the CATLM framework (Moreno & Mayer, 2007). The design of the laboratory report was guided by principles of scientific discovery learning (de Jong & van Joolingen, 1998), which refers to a highly self-directed and constructivist form of learning where students infer the characteristics of the underlying model via experimentation (de Jong & van Joolingen, 1998). The simulation for the different electric field configurations in the learning design would serve as a conceptual model for the learner. Learner's basic action would be to change certain input variables and observe the resulting changes in values of output variables. In this case, the learner would change the distance by moving the cursor (input variable) and would observe how it changes the value of the force or electric field (output variable) and the direction of the electric field (output variable).

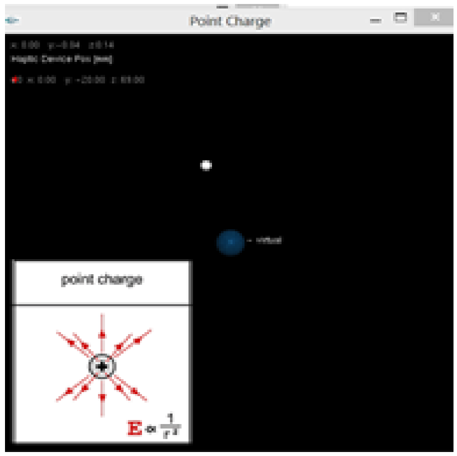
Scientific discovery learning also provided a number of methods to support learners in the discovery process including; (a) access to domain knowledge, a knowledge section in the lab report to refresh the basic concepts of electric field; (b) model progression where students started with the basic point charge simulation and then explored more complex configurations such as line charge, and ring charge; (c) embedded support and reflection in the form of questions to guide students through the inquiry process; and (d) structuring the discovery process with a sequence of experimentation steps.

4.5 Data Collection Methods

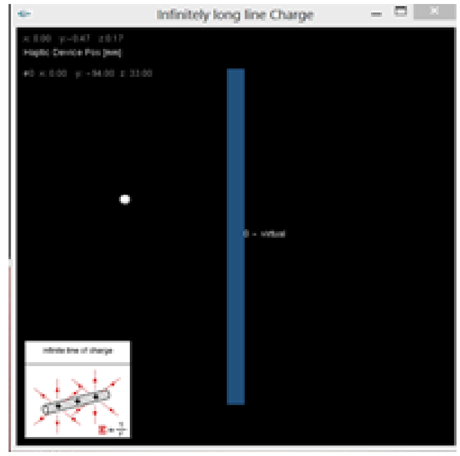
The preliminary design for the simulations contained six distributed charged configurations: (a) point charge, (b) line charge, (c) two oppositely charged parallel plates, (d) sphere charge, (e) ring charge and (f) plane charge. Figure 4-4 shows the screen shots of these simulations.

After an initial review with subject experts, it was suggested to have a coherent 2D structure for all simulations. Since sphere charge and plane charge were 3D, it was proposed to not include them in the research design in order to avoid any learning conflicts because of a combination of 2D and 3D representations. The oppositely charged simulations were not included in the final design due to time constraints.

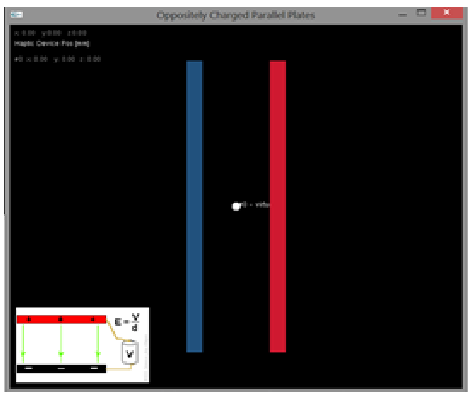
The assessment was designed to measure the conceptual understanding of the students pertaining to a general understanding of electric field strength and field lines and to understand the relationship between force and distance for the three distributed charged configurations namely: (a) point charge, (b) infinitely long line charge and (c) ring charge.



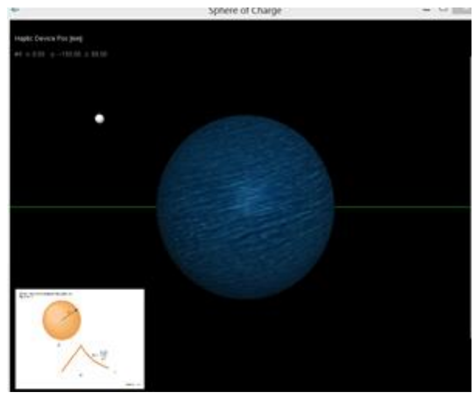
(a) Point Charge



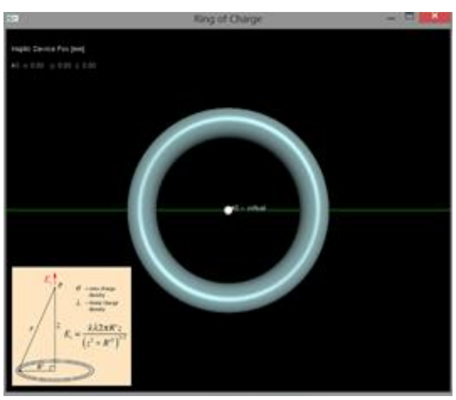
(b) Line charge



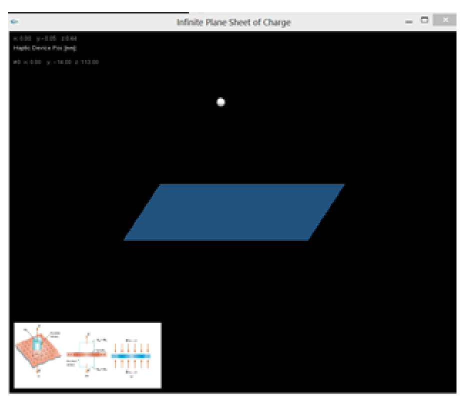
(c)Two Oppositely Charged Parallel Plates



(d) Sphere charge



(d) Ring Charge



(e) Plane Charge

Figure 4-4. Preliminary Distributed Charge Configurations

Figure 4-5 shows the sample assessment question corresponding to four categories and the learning objects associated with each of them. Several assessment instruments have been developed in previous research to gauge the conceptual understanding of students about electromagnetic concepts. Selected questions from the text books and online resources were used to probe the participant's conceptual knowledge of electric field for distributed charges. The pretest and posttest instruments were identical, and included questions from each of the three configurations (namely point, line and ring charge), consisting of 9 items. For Study One, only five questions were included. An additional expert evaluation was conducted with experts in the field of physics education. Researchers' agreement on the appropriateness of the topics and questions targeted to technology and engineering undergraduate students was used as a validation for the final instrument. Appendix C (Study One) and Appendix D (Study Two and Three) describes the assessment questions in the pretest and posttest.

4.6 Procedures

First the students were asked to fill out an introductory survey. The survey has been described in Appendix A. The introductory survey was designed to collect information about the student's major, academic level and the students' physics background.

The students explored some sample CHAI 3D simulations to get familiarized with the device (pre-training principle). Next, the students worked on a short guided learning experience involving buoyancy. The students could change the object density, liquid density and object size and feel the changes in the buoyant force. Appendix B describes the guided experience in detail.

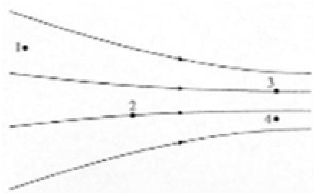
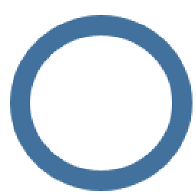
Category	Sample Questions	Learning Objective
General Understanding of Electric Field Strength and Electric Field lines	 Rank the electric field strength in order from largest to smallest. A: E1 < E2 < E3 = E4 B: E3 = E4 < E2 < E1 C: E2 = E3 < E4 < E1 D: E1 < E4 < E2 = E3	The question assesses the students understanding about electric field strengths.
Point Charge	At three times the distance from a point charge, the strength of the electric field is A. Nine times its original value. B. Three times its original value. C. One third its original value. D. One ninth its original value.	The question assesses the students understanding about Coulomb's law.
Infinitely Long Line Charge	At three times the distance from a line charge, the strength of the electric field is A. Nine times its original value. B. Three times its original value. C. One third its original value. D. One ninth its original value.	The question assesses the students understanding about the relationship between electric field and distance for an infinitely long line charge.
Ring Charge	Can you plot the direction of the electric field inside and outside a positively charged ring? 	The question assesses the students understanding the direction of field lines for a positively charged ring.

Figure 4-5. Sample Assessment Questions

The students then worked on a pretest assessment. The learner's would then be evaluated for a gain in conceptual understanding using a posttest which is identical to the pretest.

The format of the lab report was designed with the intention to provide the students with a guided learning experience. In order to maximize the learning experience with the simulations, the students were guided through their exploration process. The students worked on a lab report while they explored the three different electric field simulations (point charge, line charge and ring charge). Two transfer questions were asked corresponding to the point (Study One only) and line charge (Study One, Two and Three). Two transfer questions were asked in Study One corresponding to the point and line charge configurations: (1) It is observed that Balloon A is charged negatively. Balloon B exerts a repulsive effect upon balloon A. Would the electric field vector created by balloon B be directed towards B or away from B? Explain your reasoning. (2) Graph the magnitude of the full expression for E (electric field) vs. r (distance) for an infinitely long line charge. Does E fall off monotonically with distance? For Study Two and Study Three, only one transfer question pertaining to the infinitely long line charge was included due to time constraints. It must be noted that in all the references where line charge is mentioned, it refers to the infinitely long line charge configuration. Please refer to Appendix E for a detailed description of every component of the lab report.

Please give us any comment or observations about this laboratory experience:

Please mark with an x your level of agreement with each of the following statements:

I enjoyed learning physics concepts with haptic devices	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
Haptic devices were easy to interact with	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
The force feedback was easy to be interpreted	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
Interacting with haptic devices requires a lot of mental effort	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
Interpreting the force feedback requires a lot of mental effort	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

Figure 4-6. Student Feedback Section in Lab Report

4.7 Data Analysis

The hypothesis of the current research is that participants who experience the visuohaptic intervention gain a significant conceptual understanding about the electric fields for distributed charges. This gain is hypothesized in the form of improved test scores comparing the pre-intervention assessment of conceptual knowledge and a post-intervention assessment of the same knowledge. The data from the three studies was analyzed using both descriptive and inferential statistics. During the descriptive analysis, mean scores and standard deviations were calculated for pretest and posttest scores. The scores from the pretest and posttest were graded as (0) incorrect (1) correct for Questions 1 to 8 and (1) or (2) for Question 9. Analyses were performed for: sample pretest-posttest scores and by questions' topics namely point charge, infinitely long line charge, ring charge and general understanding of field lines and field strength. The coded data was then analyzed using inferential statistics to check if there were any conceptual gains because of the visuohaptic intervention. Cohen's d test (Cohen, 1988) was used to compute the effect size of the visuohaptic intervention. The following scale was used to interpret the effect size: (a) Weak effect size: $|d|<0.2$; (b) Weak to moderate effect size: $0.2<|d|<0.4$; (c) Moderate effect size: $0.40<|d|<0.65$; (d) Moderate to strong effect size: $0.65<|d|<0.8$; (e) Strong effect size: $0.8<|d|$ (Rubin, 2012).

In addition, the laboratory report was also used as a data collection instrument. The laboratory report was the main vehicle to guide students in their exploration of three different electric field simulations (point charge, infinitely long line charge and ring charge). All responses from the lab report were scored using a three-level rubric that assessed student wrong interpretation of repulsion force (0 points); student awareness, but somewhat incorrect mapping between the visualization and the force feedback (0.5 points); and student ability to correctly interpret the phenomenon being experienced along with a correct mapping between the visualization and the force feedback (1 point). Table 4-2 shows the rubrics used to grade the guided tasks in the lab report.

Transfer questions were assessed for incorrect interpretations (0 points), partially correct interpretations (0.5 points) and correct interpretations (1 point). Study Two and Study Three had transfer questions only for the infinitely long line charge. Due to time constraints the transfer question for the point charge was removed from the lab report. Table 4-3 shows the rubrics used to grade the transfer questions.

Table 4-2. Rubrics – Guided Tasks Lab Report

Charge Type (Code)	No explanations or misconceptions (0)	Identifies a connection, but it is either incorrect or not coherent (0.5)	Correctly identifies all the relevant components (1)
Point (P)	No answers or answers contain misconceptions. E.g. The student interprets the repulsion force as some magnetic field.	Student interprets the force feedback in the context of visualization as not proportional but relatable? 2. .."Field charge"? Decreases as we move away?	Point charge exerts force greater when closer to center than farther.
Line (L)	No answers or answers contain misconceptions. E.g. The student interprets the repulsion force as some magnetic field force.	Student interprets the force feedback in the context of visualization as not proportional but relatable? Student identifies individual scenarios, but does not interpret the difference correctly.	Line charge exerts greater force when close to the line, but the force decreases exponentially as you move away from the charge.
Ring (R)	No answers or answers contain misconceptions. E.g. The student interprets the repulsion force as some magnetic field force.	Student interprets the force feedback in the context of visualization as not proportional but relatable? Student thinks “force at center and away from ring is the same”	The force is zero at the center, increases from the center to the circumference and decreases outside the ring.

Table 4-3. Rubrics – Transfer Questions Lab Report

Category	Incorrect/ Misinterpretation(0)	Partially correct/ Logically close an explanation (0.5)	Correct. Is able to apply the knowledge correctly (1)
Transfer Question Point (TP)	Student incorrectly identifies that field vector is pointing away because A and B are unlike charges	Student correctly identifies that field vector at B is pointing towards itself, but does not provide reasoning.	Student says field vector at B is pointing towards itself because it is a negative charge.
Transfer Question Line (TL)	Incorrect graph	Identifies a negative relationship, but shows a linear relationship.	Identifies an exponential relation graphically.

Only for Study Two, a correlation analysis was done to check the relationship between time spent on a simulation and the posttest score obtained. The results from this analysis would be helpful to understand if the amount of time a student spent on a simulation has any relationship with the score the student obtains.

The comments in the feedback section shown in Figure 4-6 were grouped into different categories namely positive, negative or suggestion-oriented. Corresponding to the different categories, further sub-categories were assigned based on the similarity of comments. These categories and sub-categories are different for all the three studies. Counts for each of the sub-categories was calculated and sample responses were documented corresponding to each of these sub-categories.

Students' perceptions of the learning experience in terms of motivation, ease of use and mental effort were scored (See Figure 4-6). The student responses to the survey questions were graded on a scale of 1 to 5 (1=Strong Disagree, 2= Disagree, 3= Undecided, 4= Agree, 5=Strongly Agree) and average scores and standard deviations were calculated.

4.8 Chapter Summary

The purpose of this chapter was to describe the methodology used in the experimental study. It explains the different aspects of the research design namely the process of sample selection and describing the step-by-step procedures used in the experiment. It describes the design of the data collection instrument and provides an explanation of the statistical procedures used to analyze the data.

CHAPTER 5. STUDY ONE – ENGINEERING STUDENTS

5.1 Introduction

The first iteration of the study was planned with an intent to pilot the research design and get an initial idea about the effectiveness of the research design. Based on the feedback received from Study One, a more refined design was implemented for the two successive iterations.

5.2 Participants

Participants included nineteen undergraduate engineering students during an informal skill session. A skill session refers to an informal one-hour workshop that aims to provide practical, hands-on skills to supplement classroom instruction. Eighteen students had some background in physics, while only one student had no background in physics. Similarly four students had taken a course in electricity and magnetism the previous semester.

5.3 Data Collection and Analysis

The data collection consisted of a sub-sample of five questions from those used in the second and third iteration of the study. The selected questions focused on probing students' conceptual knowledge of electric field for distributed charges.

The pretest and posttest instruments were identical. Appendix C describes the assessment questions in the pretest and posttest and their sources.

In addition, we also explored the motivational, usability factors as well as level of mental effort associated with using haptic technology for learning. The survey included a set of five Likert-scale questions that students ranked in a scale from one to five from strongly agree to strongly disagree. Questions included (a) I enjoyed learning physics concepts with haptic devices; (b) haptic devices were easy to interact with; (c) the force feedback was easy to be interpreted; (d) interacting with haptic devices requires a lot of mental effort; and (e) interpreting the force feedback requires a lot of mental effort. Finally, an open-ended question collected students comments or observations associated with the laboratory experience. Data analysis consisted of a paired t-test to identify significant differences between pre and posttest measures and a categorical analysis of the open ended responses to the last question.

5.4 Validity Measures

Measures of validity consisted of a subject matter expert who reviewed the materials and provided his and revisions to the learning design, the simulation tools and assessment instruments. These materials were validated on content accuracy and correctness. On the basis of the evaluation by the expert, some items were revised in terms of wording to provide clarification.

5.5 Procedures

All participants started the session by providing background information and filling out the pretest. Then, students received introductory information about haptic devices and their applications and how simulations can interact with visualizations. Students were then asked to interact with two other sample CHAI 3D visuohaptic simulation and an educational simulation of buoyancy and for a period of 15 minutes and responding to two probing questions, while working on a guided questionnaire (See Appendix B). During the same session, students then switched to the instructional materials and interacted with the visuohaptic simulations exploring the new configurations. Students worked on their laboratory reports at the same time they used the simulations for approximately 35 minutes. At the end, students completed the posttest assessment.

5.6 Results

5.6.1 Measuring Gain in Conceptual Understanding

Participants' responses were coded as incorrect (0) or correct (1) and compared pre and posttest scores to identify significant differences. Table 5-1 is a summary of the descriptive and inferential statistics for the pretest and posttest measures.

Table 5-1. Descriptive Statistics for Study One

	Pretest		Posttest		Gain = Posttest - Pretest		
N	Mean	Std. Dev.	Mean	Std. Dev.	t	p-value	Mean Gain
19	2.63	1.06	3.16	1.27	2.019	.059	0.53

Results from the pretest measures suggest that overall, students from all conditions performed moderately low having approximately half of the questions correct. Considering the descriptive statistics from the posttest measures, it can be identified that students improved their performance to an acceptable level (~60%). The Cohen's effect size value (d = -0.455) suggests a moderate conceptual gain.

5.6.2 Evaluation of Lab Report

Results from the laboratory report suggest that overall students were able to make appropriate mappings between the force feedback received by the haptic and the conceptual interpretation of the force contextualized in the visualization. Similarly, most of the students achieved partial or complete understanding in the transfer question for the line charge. However, for the case of the transfer question for the point charge, a considerable number of students were unable to demonstrate an acceptable level of achievement. This result can be attributed to the point charge transfer question being based on negative charges, and since students worked on positive charges only as part of the visuohaptic simulation, many of them were unable transfer the knowledge from a positive to a negative scenario. Table 5-2 summarizes student level of achievement on the laboratory report.

Table 5-2. Descriptive statistics of student performance on the laboratory report.

Force Feedback Awareness and Mapping to Visualization				Transfer Questions	
Configuration	Point Charge	Line Charge	Ring Charge	Point Charge	Line Charge
Mean	0.74	0.79	0.63	0.55	0.61
Std. Dev.	0.35	0.25	0.37	0.50	0.39
Count of 0	2	0	3	8	4
Count of 0.5	6	8	8	1	7
Count of 1	11	11	8	10	8

Figure 5-1 shows an incorrect response to the transfer question for infinitely long cine charge. Figure 5-2 shows a partial understanding of the student, where in a linear relationship is shown instead of an exponential one. Figure 5-3 is an example of a completely correct graph, depicting a clear understanding about the relationship between electric field and distance.

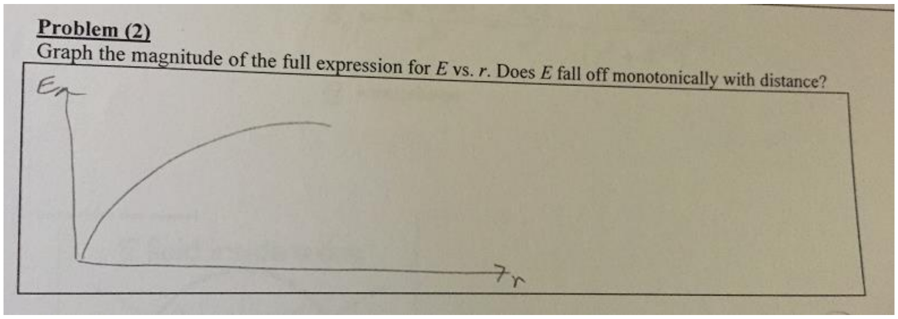


Figure 5-1. Example of incorrect graph

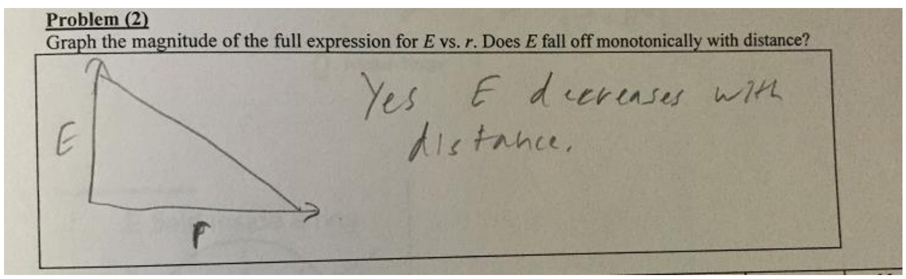


Figure 5-2. Example of a partially correct graph

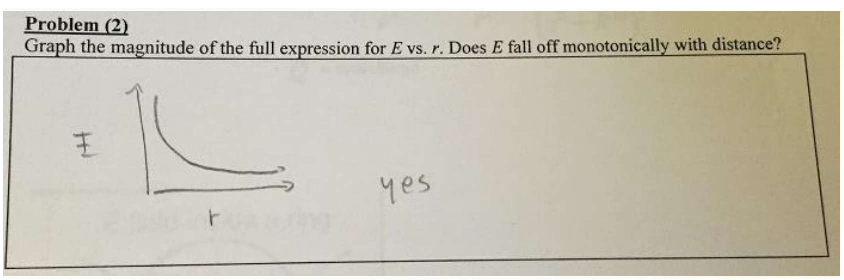


Figure 5-3. Example of a correct graph

5.6.3 Measuring Learning Perceptions

Students' perceptions of their learning experience were captured with a final open ended question. Eighteen responses received were then categorized based on similar responses. Three types of responses were identified; responses that commented on (a) the usefulness of the learning experience, (b) finding the experience as very interesting, and (c) enjoyment of the learning experience. Two types of negative responses were identified: (a) other educational methods as being better, and (b) other comment such as the need of higher fidelity of the visualization component, or finding the haptic component as distracting. Table 5-3 below summarizes the categories and the percentages of student comments that belonged to that category.

Table 5-3. Categories and Percentage Distribution of Student Feedback

Type	Category	Percentage	Sample
Positive			
	Usefulness of the learning experience	27%	"Very helpful for understanding physics concepts."
	Finding the experience as interesting	27%	"Very interesting demonstrating physics concepts."
	Enjoyment of the learning experience	17%	"It was quite fun!"
Negative			
	Other educational methods are better	17%	"Experimentation is better than school work."
	Other	12%	"The Falcon can be distracting as it is fun to play with."

5.6.4 Identifying Students Motivation, Ease of Use and Effort

Students' perceptions of the learning experience in terms of motivation, ease of use and mental effort were overall positive. The student responses to the survey questions were graded on a scale of 1 to 5 (1=Strong Disagree, 2= Disagree, 3= Undecided, 4= Agree, 5=Strongly Agree). A summary of the descriptive statistics is presented in Table 5-4.

Table 5-4. Descriptive statistics of students' responses to the motivation, usability and effort survey.

Question	Mean	Std. Dev.
I enjoyed learning physics concepts with haptic devices	4.05	0.71
Haptic devices were easy to interact with	4.10	0.46
The force feedback was easy to be interpreted	3.68	1
Interacting with haptic devices requires a lot of mental effort	2.05	0.85
Interpreting the force feedback requires a lot of mental effort	2.47	0.96

5.7 Summary of Results and Discussion

The first iteration of the study helped to assess the research design with a view to improve the quality of the design. Nineteen undergraduate engineering students participated in the study, which included a guided learning experience with the visuohaptic simulations. Though the students improved their conceptual understanding in the form of improved test scores, this improvement was not statistically significant.

In the first iteration, different strategies were implemented that aimed to maximize the learning experience by situating the learning experience in an inquiry-based approach (de Jong & van Joolingen, 1998), and enhancing it with principles of multimodal learning (Moreno & Mayer, 2007). The implementation of these two approaches in the learning design complemented each other. For example, the guided activity principle of CATLM was implemented as an inquiry approach via the laboratory report. The laboratory report also provided students with embedded support and reflection that is common to both frameworks. Finally, the learning experience was structured in such a way that it was student self-directed and consequently self-paced.

One specific element that was emphasized in the learning design, was for students to make explicit connections between the force feedback and their interpretations in the context of the simulation via the signaling principle (Mautone & Mayer, 2001). This was done via probing questions such as: "What do you feel at the center of the configuration?" "How is the force increasing or decreasing as you move away from the center?" "At which point do you feel the maximum force?" Preliminary results from this first iteration suggest that the guided learning format made the learning experience helpful, interesting and enjoyable. Analyses of the student perceptions indicated that majority of the students showed an inclination to learn more using haptic technology. On an average, the students agreed that they enjoyed using the haptics device for learning and the technology was easy to interact with. At the same time, the students disagreed that the haptic device or force feedback required a lot of mental effort. However, students were undecided about interpreting the force feedback.

Some of the student perceptions were negative, which helped to improve the quality of the overall research design for the two successive iterations of the study. The feedback from the students was considered to improve the quality of the simulations and the learning tasks. Some students perceived the guided learning experience to be very repetitive. A quantitative analysis of the lab report also suggested that even though students gained understanding about positive charged configurations, they still lacked an understanding about negative charged configurations.

CHAPTER 6. STUDY TWO – TECHNOLOGY STUDENTS

6.1 Introduction

The second iteration of the study included a more refined research approach. Based on the inputs and feedback received from Study One and after a second round of review with physics experts, the guided learning experience and the visuohaptic simulations were modified to enhance the learning experience. A major enhancement being to incorporate negative charge configurations for point charge, infinitely long line charge and ring charge. The guided learning experience (i.e., lab report) was redesigned to be more learner friendly and less redundant.

6.2 Participants

The second iteration of the study consisted of 30 undergraduate technology students who were recruited from the Polytechnic Institute of a Mid-Western University in USA. The students were paid a $20 Amazon gift card for their voluntary participation. Twenty two students had taken physics courses at undergraduate level. The courses mentioned by the students include electricity, light, and modern physics, for students not specializing in physics. Four students had no physics courses taken at undergraduate level, while four others did not report any data about the same. All the students had exposure to physics courses at high school level.

6.3 Learning Materials

The learning materials used for the second iteration were the same as in the first iteration. Based on the student feedback in the first iteration, the lab report was shortened in order to make it less redundant and repetitive. The simulations were improved and the negative charged configurations were added to each of the three configurations namely point charge, infinitely long line charge and uniformly charged ring. The addition of the negative charge scenario would enable students to feel the difference between the forces of attraction and repulsion. By merely toggling between ‘P’ and ‘N’ keys on the keyboard, the students would be able to change the simulation scenario from positive to negative and vice versa (See components (a) and (b) in Figure 6-1). Another crucial feature added to the simulations was time logging. This feature would basically log the amount of time a student spent in exploring each of the three types of simulations.

(a) Positive (b) Negative

Figure 6-1. (a) Positive and (b) Negative configurations – Infinitely Long Line Charge

6.4 Data Collection and Analysis

The transfer question for the point charge was removed from the lab report due to time constraints. The pretest and posttest were expanded on to include 10 questions versus 5 questions in the first iteration. Adding more questions would give more insights about the students learning in four categories/topics namely the general understanding of field lines and field strengths, point charge, infinitely long line charge and ring charge. In the last section of the post-test, the students were asked to rate their level of confidence and their level of agreement with the simulation being helpful (See Figure 6-2).

Please indicate your level of confidence on the accuracy of the response you have selected:	Extremely Confident	Confident	Undecided	Slightly Confident	Not Confident
Please indicate your level of agreement with the following statement: I felt that at least one of the simulations helped me to respond this question.	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

Figure 6-2. Feedback Section in Posttest

6.5 Procedures

All participants started the session by providing background information and answering the pretest (5 mins). Then, students received introductory information about haptic devices and their applications and how simulations can interact with visualizations (5 mins). Students were then asked to interact with two other sample CHAI 3D visuohaptic simulations and an educational simulation of buoyancy and for a period of 15 minutes and responding to two probing questions, while working on a guided questionnaire (See Appendix B). During the same session students then switched to the working on the lab report and interacted with the visuohaptic simulations exploring the new configurations. Students worked on their laboratory reports at the same time they used the simulations for approximately 35 minutes. At the end, students completed the posttest assessment.

6.6 Results

6.6.1 Measuring Gain in Conceptual Understanding

Table 3-1 shows the descriptive statistics associated with the pretest and posttest scores. The scores are divided into five categories: total score (Questions 1 to 9), general understanding (Questions 1 and 8), point charge (Questions 3 and 5), line charge (Questions 4 and 6) and ring charge (Questions 2, 7 and 9).

The p-value for the total score, general, point charge, line charge and ring charge is less than 0.05, indicating a significant increase in the students' conceptual understanding about these categories. Results from the pretest measures suggest that overall, students from all conditions performed moderately low having approximately half of the questions correct. Considering the descriptive statistics from the posttest measures, it can be identified that students improved their performance to an acceptable level (~70%). The Cohen's effect size value (d = -0.94) suggests a strong conceptual gain.

Table 6-1. Descriptive and inferential statistics for Study Two.

	Pretest		Posttest		Gain = Posttest – Pretest		
Category	Mean	Std. Dev.	Mean	Std. Dev.	Mean Gain	t	p-value
Total Score	5.23	2.06	7.03	1.77	1.8	4.267	0.000
General	1.00	0.64	1.37	0.61	0.37	3.266	0.003
Point Charge	1.07	0.74	1.43	0.68	0.37	2.257	0.032
Line Charge	1.1	0.71	1.53	0.68	0.43	2.765	0.010
Ring Charge	2.06	1.11	2.7	1.02	0.63	2.392	0.023

Twenty two students had a good physics background and had taken one or more undergraduate level physics courses. The courses included a combination of the courses listed below:

- PHYS 221: Electricity, light, and modern physics, for students not specializing in physics.
- PHYS 220: Mechanics, heat, and sound, for students not specializing in physics.
- PHYS 219: Electricity, magnetism, light, and modern physics for technology students

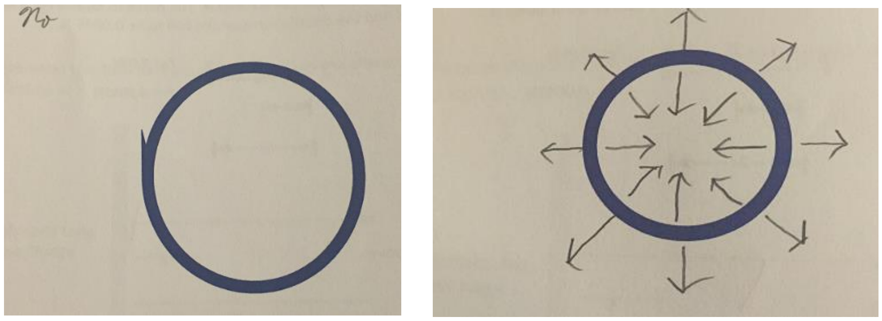
Eight students had not taken physics courses at undergraduate level and had just high school level physics background. The twenty two and eight students were segregated into two groups for further investigating the level of gain in the conceptual understanding of both these groups. As shown in

Table 6-2, on an average the twenty two students with an undergraduate level physics background scored 60% of total score in the pretest and improved their conceptual understanding significantly (p=0.006) reflected by the increase of the posttest scores to approximately 68% of the total score. On the other hand, the remaining eight students with high-school level physics background started with scoring approximately 43% of the total score and improved their posttest scores significantly (p=0.003) to approximately 76%.

Table 6-2. Scores of "Under-graduate Physics Background" Students and "High-School Physics Background" Students.

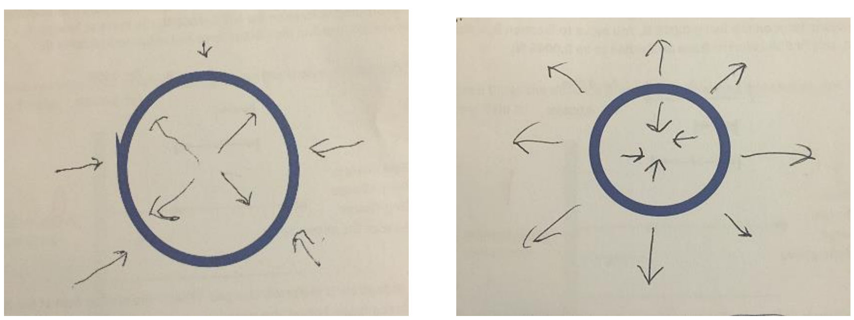
	Pretest		Posttest		Gain = Posttest – Pretest		
Category	Mean	Std. Dev.	Mean	Std. Dev.	Mean Gain	t	p-value
Undergraduate-Physics	5.59	2.08	6.82	1.79	1.22	3.029	0.006
High-School Physics	4.25	1.75	7.62	1.68	3.37	4.473	0.003

A significant improvement in the students understanding was observed in Question 9. The question required students to plot the direction of the electric field both inside and outside the positively charged ring. Analyzing the pretest scores, only 16% were correctly able to plot the directions correctly both inside and outside the field. However, the analysis of the posttest scores reveal that 84% students were correctly able to plot the direction of the electric field both inside and outside the ring charge. Figure 6-3 shows the pretest and posttest attempt for Question 10 by Student# 123. In the pretest attempt, the student had no understanding about the direction of the electric field. However, in the posttest attempt the student was able to correctly plot the direction of the electric field both inside and outside the ring. Similarly, Student# 84 initially plots the incorrect directions both inside and outside the ring in the pretest. After the visuohaptic intervention, the student was able to correctly plot the directions (See Figure 6-4).



(a) Pretest (b) Posttest

Figure 6-3. Student# 123 develops a complete understanding from no understanding



(a) Pretest (b) Posttest

Figure 6-4. Student# 84 develops a complete understanding from an incorrect understanding

6.6.2 Evaluation of Lab Report

Results from the laboratory report suggest that overall students were able to make appropriate mappings between the force feedback received by the haptic and the conceptual interpretation of the force contextualized in the visualization. The results from the lab report evaluations also suggest a greater number of students reporting a complete understanding in the point charge as compared to the line charge and ring charge simulation. Students were not able to clearly explain how the force changes as you move from center to the ring and outside the ring away from the circumference. Similarly, most of the students achieved a partial or complete understanding in the transfer question for the line charge. Table 6-3 summarizes student level of achievement on the laboratory report.

Table 6-3. Descriptive statistics of student performance on the Laboratory Report.

Force Feedback Awareness and Mapping to Visualization				Transfer Question
Configuration	Point Charge	Line Charge	Ring Charge	Line Charge
Mean	0.92	0.8	0.7	0.72
Std. Dev.	0.19	0.19	0.25	0.31
Count of 0	0	0	0	2
Count of 0.5	5	12	18	13
Count of 1	25	18	13	15

6.6.3 Measuring Learning Perceptions

Students were asked for a feedback about their experience learning with haptic technology in the last section of the lab report. Students' perceptions of their learning experience were captured with a final open ended question. Twenty nine responses received were then categorized based on similar responses. Three types of responses were identified; responses that commented on (a) the usefulness of the learning experience, (b) finding the experience as very interesting, and (c) enjoyment of the learning experience. Two types of improvement-oriented responses were identified: (a) suggesting improvements in existing simulations, and (b) other comment such as the need of higher fidelity of the visualization component, or finding issues in the way the device works.

Table 6-4 below summarizes the categories and the percentages of student comments that belonged to that category.

Table 6-4. Categories and Percentage Distribution of Student Feedback

Type	Category	Percentage	Sample
Positive			
	Usefulness of the learning experience	42%	"Definitely helps in understanding of forces needed in buoyancy and charges. Offers a more memorable experience than simply reading about it."
	Finding the experience as interesting	17%	"This was a very interesting lab experience! I am very glad I participated and got a chance to see what future education might involve. It was also fun to review my physics concepts :)"
	Enjoyment of the learning experience	17%	"Really fun! A good demo of difficult-to-recreate situations."
Improvement-Oriented			
	Suggesting improvements	10%	"It was a good tool to use in laboratories and definitely a good way to help students learn and visualize electricity. However, the haptic device could not handle some of the forces such as the negative charges where it will shake all over the place."
	Other	14%	"These tests give a good basis for physics applications. Personally, I would have enjoyed more of its initial tests as they conveyed texture and reactive forces."

6.6.4 Measuring the Effect of Time spent on Simulation

The point charge, line charge and ring charge simulation code contained a logging feature. When the students exited the simulation, a log file was created for each run, which contained the total time in seconds spent by the student on the simulation.

Due to some constraints, the logs for only 22 students out of 30 were backed up. The data in the logs contained some low time values like 9, 18, 25 and 26 seconds, which maybe because students closed and restarted the simulations during the guided activity. This may have caused the earlier log files to have been overwritten. For the purpose of analysis, such low values were omitted.

Table 6-5 shows the correlation analysis between the posttest scores of the students in the individual categories (point charge, line charge and ring charge) and the corresponding time spent on each of these simulations. As depicted in Table 6-5, the Pearson's correlation factor is between 0 and 0.2, indicating no relationship or a weak relationship between time spent and the scores achieved.

Table 6-5. Correlation Analysis – Posttest Scores vs Time spent on Simulation

Category	Pearson Correlation	Sig-2 tailed
Point Charge Posttest score and Time spent on point charge simulation	0.199	0.427
Line Charge Posttest score and Time spent on line charge simulation	0.095	0.682
Ring Charge Posttest score and Time spent on ring charge simulation	0.031	0.892

6.6.5 Identifying Students Motivation, Ease of Use and Effort

Students' perceptions of the learning experience in terms of motivation, ease of use and mental effort were overall positive. The student responses to the survey questions were graded on a scale of 1 to 5 (1=Strong Disagree, 2= Disagree, 3= Undecided, 4= Agree, 5=Strongly Agree). A summary of the descriptive statistics is presented in Table 6-6.

Table 6-6. Descriptive statistics of students' responses to the motivation, usability and effort survey.

Question	Mean	Std. Dev.
I enjoyed learning physics concepts with haptic devices	4.53	0.51
Haptic devices were easy to interact with	4.5	0.51
The force feedback was easy to be interpreted	4.47	0.68
Interacting with haptic devices requires a lot of mental effort	1.9	0.55
Interpreting the force feedback requires a lot of mental effort	2.1	0.84

6.7 Summary of Results and Discussion

The second iteration of the study was improved based on the feedback from the first iteration. With an intent to improve the research design, three major changes were made to simulations: (1) negative charge configurations were added, (b) the lab report was improved by discarding redundant questions, which made the lab report repetitive earlier and (c) the number of questions in the assessment were increased from 5 to 10 in order to get more insights about the students conceptual understanding.

Thirty students from the School of Polytechnic voluntarily participated in the study. Results from the second iteration suggest that students significantly improved their conceptual understanding. The number of positive perceptions were higher than in the first iteration. The students agreed that they enjoyed using the haptics device for learning and the technology was easy to interact with. On an average, the students agreed that they enjoyed learning physics with haptic devices, haptic devices were easy to use and the force feedback was easy to be interpreted. Also, they unanimously disagreed that interacting with haptic devices or interpreting force feedback required a lot of mental effort.

CHAPTER 7. STUDY THREE – HISPANIC ENGINEERING STUDENTS

7.1 Introduction

A third iteration of the study was conducted with undergraduate engineering technology students from a university in Peru. The intent of adding this third iteration was to understand the efficacy of using the visuohaptic intervention with a similar academic population, but possessing a different physics background and from a different demographic setting.

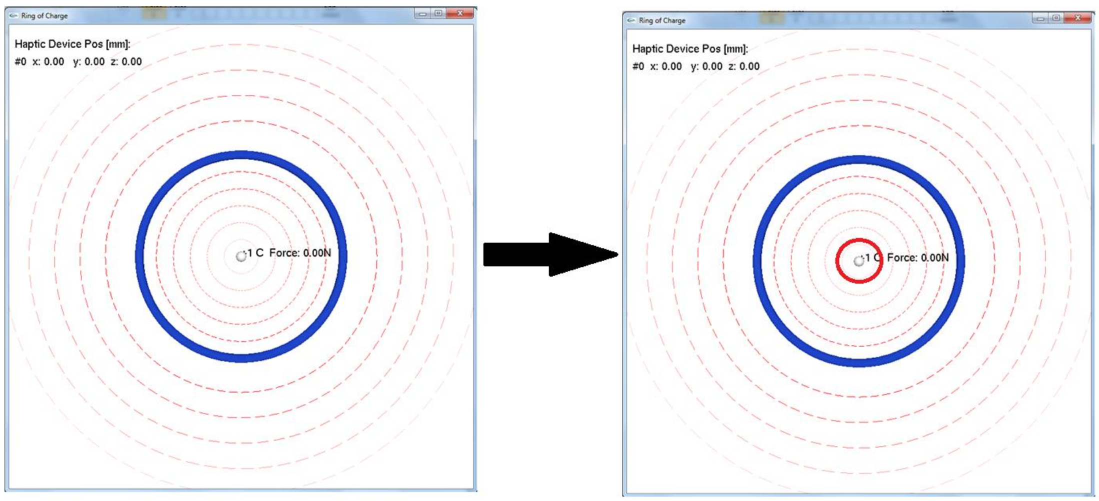
7.2 Participants

The participants were twelve engineering technology students. All the twelve students had taken physics courses at undergraduate level namely Physics I (Optical and electromagnetism topics) and Physics II (mechanics related topics). The participants were more fluent with Spanish than English.

7.3 Learning Materials

The learning materials used for the third iteration were the same as the third iteration. Since the students had more time as compared to Study One and Study Two, they explored around six sample CHAI 3D simulations. There was a small change added to the ring charge simulation to very explicitly portray that the center of the uniformly charged ring has no force.

As shown in Figure 7-1, in the ring charge simulation in the second iteration only the center point had a zero force feeling. This caused some students to assume that the force at the center of the ring charge is not zero. Hence, the simulation was modified to have a small radius where the probe would show a zero force value.



(a) Zero force felt only at center point (b) Zero force felt at all points in red circle

Figure 7-1. Changes in Ring Charge Simulation

7.4 Data Collection and Analysis

Since the students were non-native English speakers, the two assessment components (pretest and posttest) were translated to Spanish, with an intention to avoid language being a barrier to the students for understanding the questions in the assessment. The translation from English to Spanish was done by first using an online translator and then the translated document was reviewed and validated by two graduate Hispanic students with backgrounds in physics and engineering. Also, Question 6 from the assessment was omitted for the purpose of data analysis due to typing error during the translation process. Time logging data was not backed up since the students had almost an hour and a half to explore the three simulations versus 35 minutes time slot in the first and second iteration.

7.5 Procedures

The same procedures were used as in Study Two, the only exception being the time allotted for the study was increased. Instead of one hour, this study was conducted over a period of two and a half hours in the form of two sessions:

- Session 1: Haptics pre-training and buoyancy simulation (1 hour and 15 mins)
- Session 2: Electric Field Simulations (1 hour and 15 mins)

7.6 Results

7.6.1 Measuring Gain in Conceptual Understanding

Table 7-1 below shows the descriptive statistics associated with the pretest and posttest scores. The scores are divided into five categories: total score (Questions 1 to 9), general understanding (Questions 1 and 8), point charge (Questions 3 and 5), line charge (Question 4) and ring charge (Questions 2, 7 and 9). The p-value for the total score, point charge and ring charge is less than 0.05, indicating a significant increase in the students' conceptual understanding about these categories. Results from the pretest measures suggest that overall, students from all conditions performed moderately low having approximately 44% of the questions correct. Considering the descriptive statistics from the posttest measures, it can be identified that students improved their performance to an acceptable level (~68%). The Cohen's effect size value (d=-1.072) suggests a strong conceptual gain.

Table 7-1. Descriptive Statistics for Different Question Categories

	Pretest		Posttest		Gain = Posttest – Pretest		
Category	Mean	Std. Dev.	Mean	Std. Dev.	Mean Gain	t	p-value
Total Score	3.92	2.15	6.08	1.88	2.17	5.11	0.000
General	1.33	0.65	1.25	0.75	-0.08	-0.561	0.586
Point Charge	0.50	0.67	1.08	0.67	0.58	2.55	0.027
Line Charge	0.42	0.51	0.83	0.39	0.42	2.159	0.054
Ring Charge	1.67	1.15	2.92	0.99	1.25	5.00	0.000

The line charge shows an improvement in the conceptual understanding, though not statistically significant. Also, the low p-value could be attributed to the fact that the line charge category just included a single question for the third iteration. Question 6 was discarded from the data analysis due to a typing error. Seven out of twelve students answered the question about ranking electric fields incorrectly (See Figure 7-2 below for Question 1). Since the students explored the simulations which do not provide a visual representation of the field lines, they may have not been able to grasp the concept of ranking of electric field strengths. This problem was not noticed with the students in Study Two.

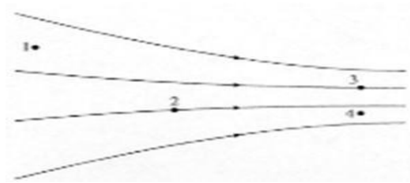


Figure 7-2. Question 1 in Assessment – "Rank the strengths of the electric fields at points 1, 2, 3 and 4"

7.6.2 Evaluation of Lab Report

Results from the laboratory report suggest that overall students were able to make appropriate mappings between the force feedback received by the haptic and the conceptual interpretation of the force contextualized in the visualization. The results also suggest a greater number of students reporting a complete understanding in the point charge and line charge simulations as compared to the ring charge simulation. Students were not able to clearly explain how the force changes as you move from center to the ring and outside of the ring away from the circumference. Similarly, most of the students achieved a partial or complete understanding in the transfer question for the line charge. Table 7-2 summarizes student level of achievement on the laboratory report.

Table 7-2. Descriptive statistics of student performance on the laboratory report.

Force Feedback Awareness and Mapping to Visualization				Transfer Question
Configuration	Point Charge	Line Charge	Ring Charge	Line Charge
Mean	0.92	1	0.71	0.62
Std. Dev.	0.2	0	0.26	0.38
Count of 0	0	0	0	2
Count of 0.5	2	0	7	5
Count of 1	10	12	5	5

7.6.3 Measuring Learning Perceptions

Students' perceptions of their learning experience were captured with a final open ended question. Twelve responses received were then categorized based on similar responses. Twelve responses were identified; responses that commented on (a) the usefulness of the learning experience, (b) finding the experience as very interesting.

None of the students reported a negative or suggestion-oriented perception. Table 7-3 below shows the different categories and the percentages of student comments that belonged to that category.

Table 7-3. Categories and Percentage Distribution of Student Feedback.

Type	Category	Percentage	Sample
Positive			
	Usefulness of the learning experience	58%	"I think we have more experience with haptic devices and with more interacting things we learn more with less time. Haptic technology has the potential to teach a lot of topics in education and to create more immersive games."
	Finding the experience as interesting	42%	"It was a great experience and I have learnt a lot doing the experiments. I like practical classes because it makes me understand better the functionality of the things."

7.6.4 Identifying Students Motivation, Ease of Use and Effort

Students' perceptions of the learning experience in terms of motivation, ease of use and mental effort were overall positive. The student responses to the survey questions were graded on a scale of 1 to 5 (1=Strong Disagree, 2= Disagree, 3= Undecided, 4= Agree, 5=Strongly Agree). A summary of the descriptive statistics is presented in Table 7-4.

Table 7-4. Descriptive statistics of students' responses to the motivation, usability and effort survey.

Question	Mean	Std. Dev.
I enjoyed learning physics concepts with haptic devices	4.42	0.51
Haptic devices were easy to interact with	4.5	0.52
The force feedback was easy to be interpreted	4.25	0.45
Interacting with haptic devices requires a lot of mental effort	2.83	0.83
Interpreting the force feedback requires a lot of mental effort	3.08	1.08

7.7 Summary of Results and Discussion

The third iteration of study was conducted with 12 students from a different demographic setting. Since this population was not a native English speaking population, the assessments were translated to Spanish to overcome the language barrier. The third iteration also had a longer duration, so students got a more hands-on experience with the haptic device. The same visuohaptic intervention was applied and the results suggest that the students also significantly increased their conceptual understanding about electric fields for distributed charges. The students unanimously responded with a series of positive perceptions, indicating that they had fun and enjoyed the learning experience. There was no increase in the student's understanding in the category of general understanding of electric field lines and field strength. This indicates that students may still need an additional aspect showing the field lines curvature embedded in the visual component of the simulation. On an average, the students agreed that they enjoyed learning physics with haptic devices, haptic devices were easy to use and the force feedback was easy to be interpreted. Also, on an average students were undecided if interacting with haptic devices or interpreting force feedback required a lot of mental effort.

CHAPTER 8. DISCUSSION

8.1 Discussion

Three iterations of the study were conducted to check for conceptual gains among three different types of populations and their backgrounds. Table 8-1 provides a summary for all the three studies. The results indicate that all the groups started at the same level with the students achieving a 50% score in the pretest. The posttest mean scores indicate that the students from Study One achieved 63% of the total score in the posttest, whereas students from Study Two and Study Three achieved approximately 70% and 67% of the total scores in the posttest respectively. Study Two and Study Three indicate a significant increase in the conceptual understanding of the students.

One-way ANOVA analysis between the pretest, posttest and mean gains of the three groups suggests:

- There were no significant differences in the pretest scores (p=0.439) among the three groups
- There were no significant differences in the posttest scores (p=0.510) among the three groups
- There were no significant differences in the gain (p=0.233) among the three groups

Table 8-1. Descriptive statistics for Study One, Study Two and Study Three

		Pretest		Posttest		Gain = Posttest – Pretest		
Sample Size	No. of Questions	Mean	Std. Dev.	Mean	Std. Dev.	T	p-value	Mean Gain
19	5	2.63	1.06	3.16	1.27	2.019	.059	0.53
30	9	5.23	2.06	7.03	1.77	4.267	0.000	1.8
12	8	3.92	2.15	6.08	1.88	5.11	0.000	2.17

The learning perceptions analyses of Study One indicates majorly positive comments and some negative comments. The comments indicated that the learning tasks were very repetitive and some indicated that other educational methods or experimentation is better than the visuohaptic intervention. Revisions to the second iteration were made to incorporate the comments and feedback received after the first iteration. A major enhancement was made to include the negative charge configurations. Learning perceptions for Study Two contained mostly positive comments and some suggestion-oriented comments. The third iteration design was very similar to second iteration with a minor change in the ring charge simulation and an increased time duration. The learning perceptions were unanimously positive for the third iteration. The results about learning perceptions concur with other research studies where the students respond expressing interest and enthusiasm about using the haptic technology (Pantelios et al., 2004).

The usability and effort survey for all the three studies suggests that students enjoyed the learning experience. Students from all the three study groups felt that it was easy to use the haptic device, though they were undecided about the ease of interpretation of the force feedback. Adding some more visual-aid to the simulations might help students to make proper connections between the force feedback component and the concepts.

8.2 Implications for Research

Haptics in education is large territory which remains unexplored. More research is needed to recognize the different forms of interactions that can take advantage of the haptic technology. That is, we need to find new uses or new movements to interact with that go beyond the uses of a computer mouse. Similarly, we need to identify new learning strategies that can support learners in encoding or translating haptically-gained knowledge into conceptual understanding.

It appears that the potential promise and outcomes of visuohaptic environments suggest that they may be related to multiple factors including the requirements of the task to be performed, the learning context, semantics of the science concepts to be learned, and the interactive affordances of the technology. For instance, the Schönborn et al. (2011) findings allude to the fact that precise co-location of the 3D visual object and haptic volume assisted in a favorable cross-modality for performing the task, which suggests that in this case the bimodal integration was beneficial for conceptual understanding. In this vein, other educational research has not always revealed a significant conceptual benefit of bimodal visual-haptic processing (Jones & Magana, 2015). It appears that the nuances of different visuohaptic set-ups and corresponding tasks have a remarkable influence on the measured outcomes.

8.3 Implications for Teaching

Due to advances in haptic technology, virtual simulations combined with force feedback can add a whole new outlook towards education. Traditional methods of teaching are now being supplemented with computer-assisted teaching methods. Instructors should imbibe different pedagogical approaches and design principles that can help them to effectively use computer simulations for learning; where a combination of direct instruction and discovery learning approaches may be some of the most effective ways (Klahr & Nigam, 2004). In the present study discovery learning approaches were primarily used. Combining both approaches may enable students to benefit more from the learning process in general, and from the haptic feedback specifically. Students frequently learn the theoretical aspects of concepts in a traditional lecture based approach. In this process, they often do not understand how the theoretical constructs are applied in practical scenarios. Incorporating haptic technology with computer simulations stimulates a deep-seated understanding about difficult concepts among students and especially those students who are kinesthetic learners. Many learners are kinesthetic learners (approximately 15% of the population) and find it difficult to learn by merely reading or listening (Coffield et al., 2004). Haptics may provide an approach which aims to inculcate the aspect of learning by doing. Sometimes, the traditional teaching approaches can prove to be inefficient and ineffective for those who learn best by using touch. Haptic technology has the potential to be an excellent training tool and assist learners in exploring constructs ranging from nano to macro world.

Haptics technology has geared towards into the gaming industry for a more commercial use, including joysticks and steering wheels. These devices could be used to build engaging educational games and there has been a lot of endeavor to bring haptic technology into a classroom environment.

The Novint Falcon (Novint Technologies, Inc.) is an inexpensive haptic device which has been primary developed to be used in 3D games. It can handle a peak force of around 10 N. As compared to many other expensive devices like the Phantom, Falcon has much fewer features. But the cost of the device makes it affordable to be used in a classroom or laboratory session.

8.4 Implications for Learning

Many of the traditional educational approaches have laid more emphasis on the visual and auditory components within learning. This has created a learning drawback for tactile and kinesthetic learners. Haptics has paved way to an entirely different learning style providing many students with the best opportunity to learn. Additionally, haptics can improvise learning even for visual and auditory audience. Haptics can enrich the learning experience in a wide range of areas ranging from biology, chemistry and physics and helping students to improve their understanding of the difficult-to-recreate concepts at hand.

The concept of virtual laboratories endorses the idea of using simulations to investigate unobservable phenomena, which may not be possible by using physical investigation. Virtual laboratories enable students to try out a number of scenarios which are limited in regular physical laboratory settings. This kind of virtual setting helps students compare, contrast and link different scientific phenomena (De Jong, Ling, Zacharia, 2013).

In some of the recent research, simulations have been combined with haptic devices. Unlike CATLM framework which guides the current research, the theory of embodied learning suggests that bodily experiences are an integral component to developing conceptual reasoning, where the knowledge constructed is closely coupled with sensorimotor skills (Wilson, 2002). Reiner (1999) suggests that tactile sensations can possibly motivate learners to access and assimilate embodied knowledge into their cognitive processing of unobservable phenomena. When learners experience a combined effect of visual and haptic representation of electric field concepts, it has the potential to instill a deep understanding of such invisible concepts.

From a cognitive perspective and keeping in mind the nature of current learning environment, there needs to be research done to assess if students are prepared to transition into using the haptic technology. The novelty associated with the device can distract the learner from the intent of the learning experience. It is inevitable that the students nowadays are becoming very familiar to using newer technologies. Care needs to be taken while integrating haptics in learning environments to avoid the problems of cognitive overload (Sweller, 1988) and split-attention effect (Mayer & Moreno, 1998). Even though the haptic technology seems useful, the novel experience and the “wow” factor can lead to cognitive overload. To avoid these issues leading to an efficient learning experience, guiding and training students on using the device would be an important training step. The pre-training will help students overcome any “wow” factor and focus their attention on the concept they learn. This training or guidance can result in students' ability to perceive force variations more readily and be able to translate them conceptually.

CHAPTER 9. CONCLUSION

9.1 Conclusions

Results from this three iteration study suggests that the educational potential of the haptic technology for conceptual understanding by touch needs further investigation. We hypothesized that the force feedback component of haptics would contribute to an improved conceptual understanding of the fundamentals related to electric field for distributed charges. Our results from the second and third iterations support the expectation. We found that students from the Study Two and Study Three improved their understanding of the concepts of electric fields for distributed charges as shown by the statistically significant increase from pretest to posttest. We attributed these changes to the theoretical framework of CATLM and the principle of scientific discovery learning which guided the research design to incorporate a guided activity principle in the form of an inquiry approach. This helped students make explicit connections between the force feedback received and the visualization component of the depicted science concepts. Preliminary results from all the three iterations of the current research showed significant positive results, but a more rigorous design with more students is still needed to validate the usefulness and advantage of using the haptic technology for creating a cognitive impact.

9.2 Limitations

The present study poses several limitations. In all the three studies, the laboratory session was not a part of the regular curriculum. The students participated to get either an extra credit or participated as a part of an additional assignment they had volunteered for. It is hard to judge if students put in their best efforts to perform well in the assessments associated with the study. Embedding the present study into an existing curriculum will probably yield more value added results and observations. The present study did not evaluate the performance of the visual only scenario as a control group. Hence, it is difficult to segregate how much students benefitted from the visual component and how much they benefitted from the haptic component. Since the present study was largely quantitative in nature, another aspect to explore would be a qualitative perspective to understand the students learning process with the visuohaptic simulations.

9.3 Future Work

Future work includes considering a qualitative approach to explore additional aspects of conceptual understanding using interview or think-out-loud protocols. Using a more open-ended approach will help to get deeper insights of the students misconceptions and allow the researcher to follow the trail of thoughts of the learner. Ensuring that the haptic modality is given more focus in the instruction and assessment components will be an important aspect of the future work. Additionally, we need to identify different learning principles that strategize to integrate the sense of touch for learning different scientific concepts. Another interesting aspect to explore would be to calibrate different force feedbacks for different scenarios to enable students finitely distinguish between different configurations (e.g. constant for plane charge, linear decrease for infinitely long line charge and quadratic decrease for point charge (Neri et al., 2015). The learning materials will also be enhanced to support constructivist learning approaches with a focus on problem-based learning or inquiry-based learning strategies. This study also provides a basis for future studies using a larger sample size. The potential educational use of haptic technology in science education is still in its infancy, and the evidence suggests that if used appropriately, it can have an enabling potential in supporting conceptual understanding. Further research is needed in this field to explore the different approaches of using haptic technology to enhance teaching and learning.

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APPENDICES

Appendix A Introductory Survey

Student Id: Lab Session #__Table #__

Please indicate your Major:

- Physics
- Chemistry
- Mechanical Engineering
- Materials Engineering
- Other

Please indicate your academic level:

- Freshmen
- Sophomore
- Junior
- Senior
- Graduate Student

Please tick corresponding to the appropriate answer:

I feel confident about my understanding of physics concepts.				
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
I feel confident about my understanding of electric fields				
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
I know about the haptic technology				
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
I have a strong liking for physics				
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

1. Please list the physics courses you have taken at the undergraduate or graduate levels.

2. Please provide a scientific explanation of why some objects float when immersed into liquids, while others sink:

Appendix B Buoyancy Guided Study

Student Name: Lab Session # ___Table #___

Part I. Experiment and Observations:

Test the following different scenarios and record your observations:-

1. Exp. 1: Without making any changes to the slider in the "Play Room" menu
   a. Write your observations about the force required to move the object in the liquid.

2. Exp. 2: Change the liquid density slider to 0.5,
   a. Write your observation about the changes in the liquid level and the force needed to move the object.
   b. Is more or less force required than in Exp. 1? Please describe or interpret the force feedback (the feel) in the context of the simulation.

3. Exp. 3: Now change the object density slider to 0.55.
   a. Write your observation about the changes in force needed to move the object.
   b. Is more or less force required than in Exp. 1 and Exp. 2? Please describe or interpret the force feedback (the feel) in the context of the simulation.

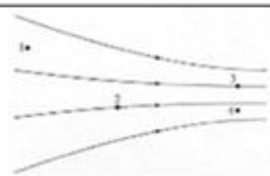
4. Exp. 4: Change the object size to 1.0.
   a. Write your observation about the changes in the liquid level and the force needed to move the object.
   b. Is more or less force required than in Exp. 3?
   c. What do you feel? Please describe your experience of the force feedback as compared to Exp 1, 2 and 3.

Part II. Conceptual question:

1. Please provide a scientific explanation of why some objects float when immersed into liquids, while others sink:

2. What are all the variables or factors that determine when an object will float or sink when immersed into a liquid?

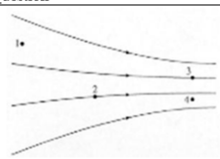
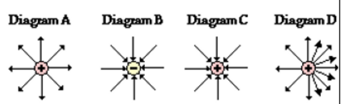
Appendix C Study One: Pre-Post Assessment

Question	Source
 1. Rank the electric field strength in order from largest to smallest. A: E1 < E2 < E3 = E4 B: E3 = E4 < E2 < E1 C: E2 = E3 < E4 < E1 D: E1 < E4 < E2 = E3	http://faculty.spokanefalls.edu/InetShare/AutoWebs/miker/Physics%20202/Chapt%2027,2/27_WorkBookSolutions.pd
2. A **hollow metal ring** of radius r carries charge q (See figure below). Consider an axis straight through the center of the ring. At what point(s) along this axis is/are the electric field equal to zero?  A. Only at the center of the ring B. Only at the center of the ring, and a very long distance away C. Only along the axis shown in the figure D. A distance r away from the center E. None of the above	http://www.education.com/study-help/article/physics-electricity-magnetism-practice-exammultiple/
3. At three times the distance from a point charge, the strength of the electric field is A. Nine times its original value. B. Three times its original value. C. One-third its original value. D. One-ninth its original value.	Question added by researcher on recommendation of the subject matter expert
4. At three times the distance from a line charge, the strength of the electric field is A. Nine times its original value. B. Three times its original value. C. One-third its original value. D. One-ninth its original value	Question added by researcher on recommendation of the subject matter expert
5. Can you plot the direction of the electric field inside and outside a positively charged ring? 	Question added by researcher on recommendation of the subject matter expert

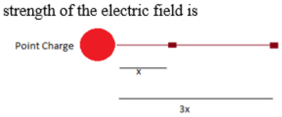
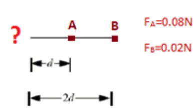
Appendix D Study Two: Pre-Post Assessment

Session# __ Table#__

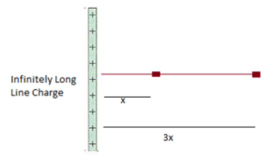
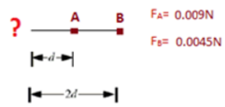
General Understanding Questions

Question	Source
 1. Rank the electric field strength in order from largest to smallest. A: E1 < E2 < E3 = E4 B: E3 = E4 < E2 < E1 C: E2 = E3 < E4 < E1 D: E1 < E4 < E2 = E3	http://faculty.spokanefalls.edu/InetShare/AutoWebs/miker/Physics%20202/Chapt%2027,2/27_WorkBookSolutions.pd
8. Several electric field line patterns are shown in the diagrams below. Which of these patterns are incorrect?  A. All of the above B. Diagram A and C C. Diagram A and B D. Diagram C, D and E E. None of the above	http://www.physicsclassroom.com/class/estatics/Lesson-4/Electric-Field-Lines]

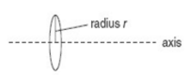
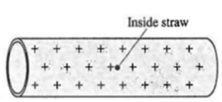
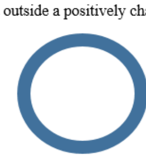
Point Charge Questions

Question	Source
1. At three times the distance from a point charge, the strength of the electric field is  A. Nine times its original value. B. Three times its original value. C. One-third its original value. D. One-ninth its original value.	Question added by researcher on recommendation of the subject matter expert
5. You stand at location A, a distance d from the origin, and hold a small charged ball. You find that the electric force on the ball is **0.08 N**. You move to location B, a distance 2d from the origin, and find the electric force on the ball to be **0.02 N.** Indicate the type of charge represented by "?".  A. Line Charge B. Point Charge C. Ring Charge D. None of the above	http://www4.ncsu.edu/~beichner/PY208/Docs/resources/Clicker%20Questions/Clicker%20Questions.html

Infinitely Long Line Charge Questions

Question	Source
2. At three times the distance from a line charge, the strength of the electric field is  A. Nine times its original value. B. Three times its original value. C. One-third its original value. D. One-ninth its original value.	Question added by researcher on recommendation of the subject matter expert
6. You stand at location A, a distance d from the origin, and hold a small charged ball. You find that the electric force on the ball is **0.009 N**. You move to location B, a distance 2d from the origin, and find the electric force on the ball to be **0.0045 N.** Indicate the type of charge represented by "?".  A. Line Charge B. Point Charge C. Ring Charge D. None of the above	http://www4.ncsu.edu/~beichner/PY208/Docs/resources/Clicker%20Questions/Clicker%20Questions.html

Ring Charge Questions

Question	Source
2. A **hollow metal ring** of radius r carries charge q (see figure below). Consider an axis straight through the center of the ring. At what point(s) along this axis is/are the electric field equal to zero?  A. Only at the center of the ring, and a very long distance away B. Only along the axis shown in the figure C. A distance r away from the center D. None of the above	http://www.education.com/study-help/article/physics-electricity-magnetism-practice-exammultiple/
6. A **hollow soda straw** is uniformly charged. What is the electric field at the center (inside, as shown in the figure below) the straw?  A. Zero B. Infinite C. A non-zero value D. None of the above	http://faculty.spokanefalls.edu/InetShare/AutoWebs/miker/Physics%20202/Chapt%2027,2/27_WorkBookSolutions.pdf
9. Can you plot the direction of the electric field inside and outside a positively charged ring? 	Question added by researcher on recommendation of the subject matter expert

Appendix E Lab Report (Study Two and Three)

Session# ___ Table#_____
Lab – Electric Field of Distributed Charges

OBJECTIVES
In this lab you will:

- Learn to calculate and display the electric field for point charge.
- Learn to calculate and display the electric field for infinitely long line charge.
- Learn to calculate and display the electric field for ring charge.

Electric fields created by single particles are both simple to envision and simple to calculate. However, the electric fields created by an arrangement of particles are much harder to visualize – and extremely tedious to calculate. The visuohaptic simulations are an excellent way to represent the complex arrangements of particles and modeling their electric fields.

<u>Point Charge</u>
Run the pointcharge.exe and observe the force you feel at points A, B and C. Position your cursor at point A, B and C.
a. Check the force at point A.

A.1 Write your initial observation? What do you feel? How do you interpret the force in the context of the visualization?

b. Check the force at point B.

B.1 Write your initial observation? What do you feel? How do you interpret the force in the context of the visualization?

c. Check the force beyond point C.

C.1 Write your initial observation? What do you feel? How do you interpret the force in the context of the visualization?

d. What is the difference or relationship between the forces felt in points A, B and C. (Does it rapidly increase or decrease?)

e. Press ‘N’ to change the charge on the point charge from positive to negative. How does the force change?

Press ‘X’ to exit the simulation.

Infinitely Long Line Charge

Run the lineCharge.exe and observe points A and B. Position your cursor at point A and B

a. Check the force at point A.

A.1 Write your initial observation? What do you feel? How do you interpret the force in the context of the visualization?

b. Check the force at point B.

B.1 Write your initial observation? What do you feel? How do you interpret the force in the context of the visualization?

c. What is the difference or relationship between the forces felt in points A and B.?

d. Press ‘N’ to change the charge on the point charge from positive to negative. How does the force change?

Press ‘X’ to exit the simulation.

Problem (1)
Graph the magnitude of the full expression for electric field *E* vs. *r (distance)* for the line charge. Does *E* fall off monotonically with distance?

Please indicate your level of confidence on the accuracy of the response you have selected:	Extremely Confident	Confident	Undecided	Slightly Confident	Not Confident
Please indicate your level of agreement with the following statement: I felt that at least one of the simulations helped me to respond this question.	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

Ring Charge
Run the ringCharge.exe and observe points A, B and C. Position your cursor at points A, B and C and record your observations.

a. Check the force you need to move from the center of the ring to point A.

A.1 Write your initial observation? What do you feel? How do you interpret the force in the context of the visualization?

b. Check the force you need to move from the circumference to point B.

B.1 Write your initial observation? What do you feel? How do you interpret the force in the context of the visualization?

c. What is the difference or relationship between the forces felt in scenarios (a) and (b)?

d. Press ‘N’ to change the charge on the point charge from positive to negative. How does the force change?

Press ‘X’ to exit the simulation.

Final Reflection

Please give us any comment or observations about this laboratory experience:

Please mark with an x your level of agreement with each of the following statements:

I enjoyed learning physics concepts with haptic devices	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
Haptic devices were easy to interact with	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
The force feedback was easy to be interpreted	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
Interacting with haptic devices requires a lot of mental effort	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
Interpreting the force feedback requires a lot of mental effort	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree