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Students' Reasoning with Haptic Technologies: A Qualitative Study in the Electromagnetism Domain

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STUDENTS' REASONING WITH HAPTIC TECHNOLOGIES:

A QUALITATIVE STUDY IN THE ELECTROMAGNETISM DOMAIN

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of

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Dedicated to my beloved parents and my loving husband.

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TABLE OF CONTENTS

Page

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

LIST OF ABBREVIATIONS

E&M – Electro-Magnetism

PhET – Physics Education Technology

TEAL – Technology Enabled Active Learning

GLOSSARY

Creswell, J. W. (1998). *Qualitative inquiry and research design: Choosing among five traditions*. Thousand Oaks, CA: Sage Publications.

Computer Simulation – "A program that contains a model of a system (natural or artificial; e.g., equipment) or a process" (De Jong and van Joolingen, 1998, p. 180)

Constructivism – "an underlying premise is that learning is an active process in which learners are active sense makers who seek to build coherent and organized knowledge" (Mayer, 2004, p. 14).

Discovery Learning – A learning environment "in which students are free to work with little or no guidance" (Mayer, 2004, p.14).

Embodied Cognition – "The emerging viewpoint of embodied cognition holds that cognitive processes are deeply rooted in the body's interactions with the world" (Wilson, 2002, p.625).

Haptics – "Haptics means the sense of touch and involves the science of incorporating this and the interaction with the external environment through touch" (Diego, Cox, Quinn, Newton, Banerjee & Wolford, 2012, p.156).

ABSTRACT

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With abundant applications in the medical training and entertainment industry, haptic technology is slowly making its way into the realm of science education, particularly in conveying abstract and non-visible concepts. Electric field is one such abstract concept. Past studies have shown that learning concepts such as electric fields in a traditional classroom can be quite challenging since students have a hard time visualizing the phenomena and applying its effects to reason. Furthermore, these concepts are the building blocks for more complex concepts such as matter and molecular interactions. Visuo-haptic devices provide a great platform to enable students to visualize and 'feel' these invisible forces through well designed simulations. The theory of embodied cognition poses that human body's sensorimotor experiences with the environment is critical to build conceptual knowledge. This research study explored undergraduate students' embodied experiences with haptic devices and their perceptions of learning electric fields with the help of visuo-haptic simulations. The results from the study using think-aloud protocol suggest that students were not only able to translate the haptic feedback to gain conceptual understanding of electric field concepts, but were also able to represent these concepts through more accurate and complete electric field diagrams.

CHAPTER 1. INTRODUCTION

Human beings experience the environment through multiple senses: hear, see, touch and smell (Smith & Gasser, 2005). When interacting with the environment, humans associate every object's attributes to one or more of these senses. Take for an instance, a flower. Different characteristics of the flower, like the way it smells, the texture of the petals, leaves and stem, the colors and shape of the flower communicate through different sensorimotor channels. On the other hand, when we encounter objects in the virtual space, very little communication happens through 'touch.' However, recent advancements in technology in the form of haptic devices have added the additional dimension of touch to virtual objects.

The last few decades have seen a rise in research focus in the use of haptic technology in science education, particularly to convey abstract and sub-microscopic concepts. The purpose of this research was to qualitatively explore undergraduate students' perceptions and experiences when they learn electric field concepts with haptic simulations.

1.1 Background

Electric field is an abstract concept. It is a fundamental component of the electromagnetism domain. Furthermore, these are the building blocks for more complex concepts such as matter and molecular interactions. However, students have a difficult time visualizing these abstract concepts. This is one of the areas where simulations can help students assimilate these concepts. Simulations enable students to imagine and visualize abstract concepts that are intangible and invisible to human eye. Haptic simulations not only help students visualize, they also add the element of 'touch' and therefore have the capability to enrich the learning experience. They make the "hands-on" educational experience truly complete.

Haptics, derived from the Greek word 'haptikos,' is defined as the ability to touch or grasp. Haptic technologies integrate the sense of touch to virtual objects, thereby giving a realistic feel of the virtual environment. It gives the users the ability to feel the texture (tactile) of the virtual object along with the force feedback (kinesthetic) from the virtual environment. The mobile industry has embraced this technology in a big way, evident from the growing popularity of 'touch' phones around the world in the past decade. The gaming industry has evolved with the help of haptic technology. Gamers can now feel the haptic interface vibrate during collision in racing games. The haptic channel gives the end consumer a more immersive gaming experience. While haptic technology is impacting the entertainment industry in a big way, it is slowly making its way into educational settings. The technology is being used extensively in medical and dental training (Escobar-Castillejos, Noguez, Neri, Magana & Benes, 2016). For instance, it is being used to train surgeons on invasive and high risk surgeries.

1.2 Significance of the study

Numerous studies in the past have shown the significance of simulations and virtual reality as a pedagogical tool in science education (Bayraktar, 2001; De Jong & Van Joolingen, 1998; Dorn, 1989; Rutten, van Joolingen & van der Veen, 2012). Past research studies have also highlighted the difficulties that students have assimilating abstract electromagnetism concepts even after instruction (Chabay & Sherwood, 2006; Galili, 1995; Maloney, O'Kuma, Hieggelke & van Heuvelen, 2001; Tornkvist & Petterson, 1992).

Research on haptic technology in science education, although little, has seen mixed results. While students assigned to the haptics treatment group in studies by Jones, Minogue, Tretter, Negishi and Taylor (2006) and Schonborn, Bivall and Tibell (2011) gained better conceptual knowledge in their tasks than their counterparts in the non-haptics group, researchers Park, Kim, Tan, Reifenberger, Bertoline, Hoberman and Bennet (2010) did not see statistical differences in knowledge gain between the haptic and non-haptic groups.

While research on haptic technology in science education has seen a growth in the past few years, very few studies are available on haptics research related to students' cognition in concepts of electromagnetism. Studies by Park et al. (2010) and Sanchez (2011) on the impact of visuo-haptics in the electromagnetism domain reported no statistical differences between the haptics and non-haptics groups. There is no qualitative evidence, however, to understand students' experiences with haptics while learning electromagnetism. The aim of this study was to fill this void and also inform future research involving students' engagement with virtual and haptic models.

1.3 Statement of Purpose

Students have a hard time visualizing the phenomena and applying its effects to reason. As a result, students may form incomplete and incongruent mental representations of these concepts. Past studies have shown that learning concepts such as electric fields in a traditional classroom can be quite challenging (Furio & Guisasola, 1998). This study aimed to explore students' reasoning and perceptions while learning electric field concepts with the help of haptic simulations.

A constructivist or an embodied approach to physics learning is desirable. Research has shown that having students physically interact with models and simulations helps them understand concepts better. The theory of embodied cognition believes that cognition lies deep within the human body and its interaction with the environment (Wilson, 2002). It is believed that sensorimotor experiences play a crucial role in building conceptual knowledge (Host, Schonborn & Palmerius, 2013). In understanding concepts such as electric fields and forces, using the visual channel alone may not be enough. In this sense, visuo-haptic devices provide a great platform to enable students to not only visualize the concepts, but also 'feel' these invisible forces through well designed simulations. However studies involving visuo-haptic devices to compare learning gains among visuo-haptic and visual only treatments in the past have seen mixed results (Bivall, Ainsworth & Tibell, 2011; Han & Black, 2011; Sanchez, 2013). It makes one wonder about the redundancy of the addition of the 'haptic' channel and its usefulness in science education.

Very little research has been done to qualitatively understand the students' perspective on using haptic devices in learning. Operating from an interpretivist inquiry paradigm (Lather, 2006) the researcher believes that the haptic experience is subjective and students' representation and conceptual understanding of the electric fields may vary depending upon how they perceive and learn through the haptic channel. The goal of this study was to explore students' perceptions on how haptics influences their conceptualization and representation of electric fields. By analyzing the students' perception and experiences with the device, the study sought to get some insights into how haptics devices can be used in the process of learning.

1.4 Research Questions

What are undergraduate students' perceptions on learning electric fields using haptic simulations?

- How do they conceptualize haptic experiences of electric field simulations?
- How do the haptic simulations influence students' representations of electric fields and forces?
- What are their perceptions on experiences with both haptic and visuo-haptic simulations of electric field concepts?

1.5 Scope of the study

Electromagnetism is a very vast domain in modern physics that deals with complex and abstract concepts of electricity and magnetism. This study limited its scope to the concept of electric fields. The simulations designed for the study use point charges, line charges and ring charges as the underlying concepts. Magnetic fields and forces, and other electromagnetic concepts were beyond the scope of the study.

The main component of the study was the think aloud process where students were probed on how they perceived the haptic channel when they interacted with visuo-haptic simulations. The pre-test, prescribed as a part of the study, was used to assess the students' conceptual knowledge on electric fields and the scores were taken as the baseline for the analysis. The progress assessment tests were prescribed to assess any conceptual knowledge gain resulting from the haptic experience. A thorough quantitative analysis, however, was beyond the scope of the study.

1.6 Assumptions

This study was designed around the following assumptions:

- Students were screened based on their responses on the survey. It was assumed that students answered questions about their physics background truthfully.
- The underlying assumption for the data analysis was that students answered to the probes during the think aloud session honestly and based on their experience with the haptic device.

1.7 Limitations

Following were the limitations of this study:

- There are different types of haptic devices in the market. They differ in their capabilities and levels of sophistication. They range from a simple joystick for video-gaming experience to the much advanced kinds used in medical training. The haptic device used in this study is the Novint Falcon device. Students' experiences might differ with different haptic devices. This study was based on students' experiences only with Novint Falcon 3D haptic controller.
- The study included only the simulations on charges and electric field. The simulations deal only with point charges, line charges and ring charge configurations.

1.8 Delimitations

The delimitations of the study are listed below:

- Although the research focused more on the "haptic" channel, the visual component was an integral element of the simulations.
- The intent was to qualitatively explore students' perception on haptics with electric field simulations. The results discussed in the study are students' perceptions and so are not generalizable.

CHAPTER 2. LITERATURE REVIEW

This chapter on literature review is used to analyze and discuss prior work relevant to the topic in hand. This chapter is divided into three broad sections. Prior work on analyzing students' difficulties with learning and understanding electromagnetism is discussed in the first section. Past research studies using simulations and computer aided technologies as pedagogical tools for science education are discussed in the second section. The final section of the literature review is used to review and analyze prior work on the theoretical framework of embodied cognition that influenced and guided this research study.

2.1 Understanding Electromagnetism and Common Misconceptions

Electromagnetism is an abstract and complex topic in physics. It is an umbrella, encapsulating several different concepts like electric current, fields, electric force, magnetic fields and forces among other things. A number of studies in the past have highlighted students' poor conceptualization of electromagnetism concepts (Chabay & Sherwood, 2006; Galili, 1995; Maloney, O'Kuma, Hieggelke & van Heuvelen, 2001; Tornkvist & Petterson, 1992). Chabay and Sherwood (2006) attribute some of these difficulties to the transition of science education from macroscopic mechanics oriented syllabus in high school to the more abstract and microscopic concepts in the university.

Most of pre-university science education deals with mechanics, involving concepts like velocity, mass and acceleration that are typically macroscopic in nature.

Students can relate to these concepts using everyday objects. Students are introduced to the basics of electrostatics and magnetism at a young age which provides the basis of primitive mental representations of these concepts. However things get more abstract in the field of electromagnetism when it is introduced in undergraduate studies in a university. Students are bombarded with sub-microscopic and invisible particles like electrons, neutrons and abstract topics like fields and field lines (Chabay & Sherwood, 2006). Some students are able to understand these abstract concepts and make changes to their mental models of these concepts. However, most students retain the primitive mental representations and fail to transform it into a mature and correct model (Thong & Gunstone, 2008).

Furio and Guisasola (1998), while analyzing students' challenges in trying to learn these concepts, say the difficulties in learning new concepts is because of 'ontological and epistemological' reasons and not because of their preconceptions about the topic. The authors go on to explain this by pointing out the fundamental differences in Coulomb's 'action at a distance' theory and Faraday's 'field everywhere theory'. It is important to note that in modern physics, both these conceptual theories are essential to explain the charge interactions. Despite the conceptual superiority of Faraday's (or Maxwellian) theory, Coulomb's (or Newtonian) theory must be learned first to understand electric charge interactions before trying to understand electric fields (Furio & Guisasola, 1998).

As can be expected, students, having been exposed to the simpler Coulomb's conceptual theory, find it difficult to visualize and understand the more abstract electric fields concept when it is introduced in electromagnetism. Galili (1995) wrote "The introduction of the field (as it is done on the high school – college level) masks, or questions, the reciprocal character of the interaction" (p. 385).

Furio and Guisasola (1998) used questionnaires and interviews as instruments for their study with a sample of 245 students and a subset of 24 students respectively. The authors noticed that students have different meanings associated with these concepts and depending on the situation, they selected the theory that worked best for them. In the context of Coulomb versus Faraday, Furio and Guisasola (1998) also found that in situations of conflicts, especially situations involving electric fields, students tend to apply the 'action at a distance' model to explain the behavior incorrectly.

Galili (1995) in his study with 11^{th} and 12^{th} grade students with a science background, and pre-service teachers from a technology teacher college with electronics proficiency found similar results on questions involving fields. Galili (1995) concluded "Without proper instruction, students consider keeping or rejecting symmetry of interaction based on their own feelings and guesses" (p. 385).

Students are taught from the beginning to use field lines to represent electric and magnetic fields. Researchers have also noted a common misconception about field lines among students, which in turn contributes to incorrect conceptualization of electric fields. They incorrectly identified field lines as a physical entities instead of treating them as an abstraction used to explain fields (Guisasola, Almudi & Zubimendi, 2004; Thong & Gunstone, 2008; Tornkvist, Pettersson & Transtromer, 1993). When asked to identify errors in Figure 2-1, Tornkovist et al (1993) found that 85% of the participants, who were sophomores at the university enrolled in the course on electricity and magnetism, did not identify the crossing field lines in the Figure as incorrect. Guisasola et al. (2004), observed that some students explained magnetic interaction by pointing out forces between field lines caused when they cross each other.

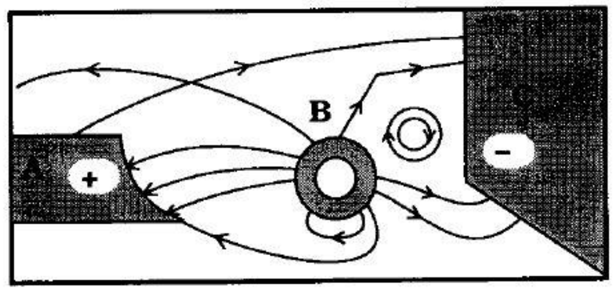


Figure 2-1. Field lines as physical entities (Tornkvist, Pettersson & Transtromer, 1993)

According to Chabay and Sherwood (2006) “Electromagnetic interactions play a central role in determining the structure of the natural world and are foundation of most current and emergent technology, a basic understanding of electricity and magnetism (E&M) is important” (p. 329). Several authors recommend replacing traditional classroom lectures in electromagnetism with more “hands-on” approaches for better conceptual gain (Furio & Guisasola, 1998; Galili, 1995). Owing to the importance in conceptual knowledge gain in students in the topics of electromagnetism, it is imperative that more research be carried out in analyzing ways to enhance students' learning experience in these subjects.

2.2 Virtual reality in education

Virtual reality as a pedagogical tool is a relatively recent phenomenon. However, this technology is revolutionizing the way learning happens in a number of ways. Virtual reality in itself is a very vast domain. The literature in this section will focus on the role of visual and haptic simulations, and computer aided games in science education.

2.2.1 Computer Simulations and Games

Student difficulties in learning abstract concepts have often been linked to their lack of motivation as they progress through school (Cordova & Lepper, 1996). The traditional classroom setting with instruction as the primary and only pedagogical practice, have only made things worse. In this context, Cordova and Lepper (1996) wrote:

> ... in school teachers often seek quite deliberately to present new material in its most abstract or decontextualized form, presumably in the belief that learning in this abstract form will promote generalization of that learning (e.g., Lave, 1988; Perkins, 1992). … By removing learning from the contexts in which both its practical utility and its links to everyday interests and activities would be obvious to children, teachers risk undermining children's intrinsic motivation for learning (p. 715).

Computer simulations and games in educational contexts, on the other hand, give a sense of control to the students. Research in the use of computer simulations and games as pedagogical tools, specifically in science education, has seen a rise in the last couple of decades (De Jong & van Joolingen, 1998; Dori & Belcher, 2005; Rutten, van Joolingen & van der Veen, 2012). On the advantage of computer simulations, especially in the context of discovery learning, authors De Jong and van Joolingen (1998) wrote, "A computer simulation is a type of computer-based environment that is well suited for discovery learning, the main task of the learner being to infer, through experimentation, characteristics of the model underlying the simulation" (p. 179). Rutten, van Joolingen and van der Veen (2012) wrote, "By placing emphasis on the learner as an active agent in the process of knowledge acquisition, computer simulations can support authentic inquiry practices that include formulating questions, hypothesis development, data collection, and theory revision” (p. 136).

Finkelstein, Adams, Keller, Kohl, Perkins, Podolefsky and Reid (2005) studied the effectiveness of replacing real laboratory equipment with computer simulations to teach simple circuits (Figure 2-2). One of the key observations in their study was on how participants who worked on the simulations were "messing about" with the simulations, which is generally not encouraged with the real laboratory equipment. This behavior suggests that students are motivated to engage and act on their curiosity. This promotes learning through exploration. Additionally, the authors observed these participants in the treatment group fared better than the ones in the control group on conceptual questions on simple circuits and were also better at manipulating the components of the circuit.

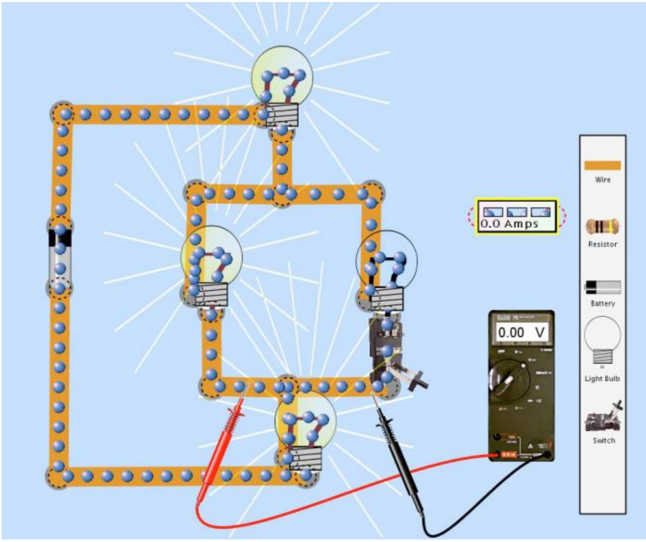


Figure 2-2. PhET Circuit construction simulation used by Finkelstein et al. (2005)

Rutten, van Joolingen and van der Veen (2012) reviewed a number of research studies that used computer simulations to teach science concepts with students in the age group 12 to 20. One of their findings was that when used in conjunction with the traditional instruction, computer simulations enhanced the learning experience. Better learning outcomes were also observed in the experimental group with simulations.

It cannot, however, be generalized that simulations always succeed in motivating and engaging students in learning activities. The design of the simulations is an essential factor to consider. Cordova and Leper (1996) compared the effects of personalization, contextualization and choice in computer games assisted learning in enhancing the intrinsic motivation of fourth and fifth grade students to learn mathematical and problem solving skills. They saw evidence for their hypotheses that when children were provided with choice and personalization they showed more engagement in the activities and higher motivation in learning the skills presented to them. When designed well, and with sufficient guidance, simulations can arouse the curiosity and interest in the students, and engage and motivate them to learn unlike traditional pedagogical practices (Rutten, van Joolingen & van der Veen, 2012).

2.2.2 Simulations in electromagnetism

Very few studies, to the best of our knowledge, have been conducted to test the educational use of simulations in electromagnetism (Dori & Belcher, 2005; Squire, Barnett, Grant & Higginbotham, 2000). Squire, Barnett, Grant and Higginbotham (2000) devised an electromagnetic simulation game called 'Supercharged' to teach basic electromagnetism concepts to 7th and 8th grade students. Apart from showing enthusiasm in playing the games, students playing the game did significantly better on post-tests when compared with the scores of participants in the control group. On the role of simulation game for learning electromagnetism, the authors wrote:

> Experiences in game worlds become experiences that students can draw upon in thinking about scientific worlds, using their intuitive understanding developed in simulated worlds to interpret physics problems. By representing complex scientific content through tangible, experienced non-textually-mediated representations, simulated worlds may also engage reluctant learners in the study of science (p. 513).

While working on the ‘Technology Enabled Active Learning’ *(TEAL)* project at MIT, Dori and Belcher (2005) studied the effects of TEAL environment on undergraduate students while learning electromagnetism. The authors recognized the students' difficulties in understanding and applying the electric fields and rightfully chose electromagnetism as the topic to study the effects of TEAL on students. TEAL is a highly collaborative and media-rich environment that includes mini-lectures, laboratory experiments and visualizations. The authors implemented a small-scale design (N=176) in fall 2001 and a large-scale (N=514) in spring 2003 to study the effects of TEAL on students' performance in electromagnetism. They compared this experimental group with a control group of students (N=121) enrolled in the traditional electromagnetism course in spring 2002. A variety of instruments ranging from conceptual tests to focus groups and observations were used to evaluate students in their cognitive, affective and social domains. One of the important results from the TEAL project was the significantly lower failure rate in the course in the experimental groups. The results of the conceptual knowledge gain among participants in the experimental groups were also significantly higher than that in the control group. These results were also observed when students within different academic levels were compared. This project is an important example in how the learning environment affects students' achievement and conceptual knowledge gain.

2.2.3 Haptic Technology for Learning

Visuo-haptic technology conveys information through both the "visual" and "haptic" channels. Visuo-haptic technology has applications in entertainment and gaming industries. It is also being used in medical science for the purposes of surgical training (Escobar-Castillejos, Noguez, Neri, Magana & Benes, 2016). It is slowly making its way into education. One of the key motivations for the use of haptic technology as a pedagogical tool in science education is the sense of 'touch' (Sanchez, 2013). Reiner (2008) calls the sense of touch to be unique - "Touch, unlike other sensory channel, is unique: It is used for both collecting touch information such as textures and shapes and simultaneously used to act on the environment" (p.74). Minogue and Jones (2006) also emphasized the importance of touch with some interesting examples from everyday life:

> Imagine living in the world without the sense of touch: Notwithstanding the known physical and social implications, formerly simple everyday tasks would become extremely difficult. Finding the doorknob in a darkened room would require the use of flashlight, and locating your keys in a purse would necessitate a visual check if it’s entire contents. … When vision alone is inadequate or not possible, touch becomes an efficient device for obtaining information (p. 318-319).

Theoretically, the sense of touch becomes even more viable in science education, especially to teach abstract and sub-microscopic concepts like electromagnetism. Haptic simulations provide a literal form of the ‘hands-on’ approach. However, past research with haptics have seen mixed results. Bivall, Ainsworth and Tibell (2010) used visuo-haptic simulations to analyze its effectiveness in molecular learning. The study was conducted on post graduate students who were divided into two groups: haptic and no haptic. Both groups had visual representation and the students in the haptic group experienced tactile feedback as well. The authors assessed student conceptual knowledge on the protein-ligand interaction and the simulations helped students visualize this interaction. Students were also evaluated on their accuracy in docking the ligand onto the protein molecule using the simulations. Both quantitative and qualitative information were collected from the students. The authors did not see a significant difference in the 'hands-on' activity or a significant conceptual knowledge gain in the pre- and post-tests comparison. However, they observed learning benefits in the qualitative analysis. It was observed that some students in both groups had misconceptions about the ligand-protein interaction to start with. However, in the post test, this misconception was not seen with haptics group. Surprisingly however, the misconception became more profound in case of the participants in visual-only group. Even those in the visual-only group who did have this misconception to start with, now had this incorrect idea about the molecular interactions. It appears that the absence of a realistic force feedback results in the development of misconceptions in students.

Schonborn, Bivall and Tibell (2011) did further qualitative analysis on the same study and reported more interesting observations. The authors noted that the student 'docking' images were more realistic in the haptics group. These students felt the force feedback, which was representative of the actual intermolecular forces. The students in the visual-only group brought their ligand closer to the protein molecule, which in reality is not possible. The advantage of the force feedback was also seen in the ligand traversal paths between the two groups.

In another study by researchers Host, Schonborn and Palmerius (2013), the authors qualitatively analyzed student conceptions about electric fields in molecular context. In this study with five 11th and 12th grade students, the authors observed that while some students built on their existing knowledge of electric fields, some others predicted a certain outcome based on their interactions with the simulations. One of the interesting aspects of this study is that the authors used the simulations to integrate concepts from physics (electric fields) and chemistry (molecular interactions), which is almost never seen in traditional classroom.

Many other interesting studies were done to analyze the effect of haptics in science education with mixed results (Abdul-Massih, Beneš, Zhang, Platzer, Leavenworth, Garcia, & Liang, 2011; Han & Black, 2011; Minogue & Jones, 2006; Wiebe, Minogue, Jones, Cowley & Krebs, 2009), fewer studies deal with haptic experiences specifically in teaching electromagnetism (Neri, Shaikh, Escobar-Castillejos, Magana, Noguez, & Benes, 2015; Park, Kim, Tan, Reifenberger, Bertoline, Hoberman & Bennett, 2010; Sanchez, 2013, Shaikh, 2015).

Park et al. (2010) used visuo-haptic simulations of point charges and their interactions in their quasi experimental study with 38 undergraduate students enrolled in an electromagnetism and optics laboratory course. The participants were assigned to either of the two groups - visuo-haptic, and visual only. Data collected through observations, interviews, content tests and surveys. The content test had questions about electrostatic fields and equipotentials. The study found significant differences between pre-test and post-test scores in both groups. However, they did not find significant differences between visual only and visuo-haptic groups. Additionally, higher percentage of students (44%) chose 'visual' as their preferred modality compared to 'hands-on' (31%). Despite the lack of quantitative evidence, the qualitative data from interviews and observations noted that many students found the force feedback helpful in the learning process. The authors also noted that students in the visuo-haptic group were observed exploring the simulations whereas similar observations were not made in the visual only group.

Sanchez (2013) conducted a similar quasi-experimental study with 66 freshmen enrolled in an electrical engineering course. The students were divided into visual-only and visuo-haptic groups. The author used simulations on bar magnets and electric dipole. The author carried out a quantitative analysis with pre-test and post-test results. The study did not find significance in conceptual knowledge gain between the two groups. Surprisingly though, the visual-only group had better gain when compared to the group with the haptic modality alone. Because of the lack of qualitative evidence in the study, it is not known why the students in the visuo-haptics group performed lower than the visual only group.

As can be seen in both these studies with visuo-haptic simulations in learning electromagnetism, qualitative evidence is key in analyzing the role of tactile feedback in learning these abstract components. Understanding student perceptions and their experiences in learning electric fields with haptic modality will throw some light on the efficacy of the haptic technology in learning electromagnetism. The goal of this research study was to address this gap in literature and thereby inform future studies in this domain.

2.3 Theoretical Framework

The theory of "Embodied Cognition" was the underlying framework for this study on student conceptualization and representation with haptic simulations. The literature reviewed in this section informed and inspired the methodology of this research.

"The emerging viewpoint of embodied cognition holds that cognitive processes are deeply rooted in the body's interactions with the world" (Wilson, 2002, p. 625). Wilson (2002) also claims that people advocating embodied theory believe that it is not the mind that processes abstract ideas, "but the body that requires the mind to make it function" (p. 625)

Reiner (1999) used the analogy of a tennis player to relate tacit knowledge to embodied learning and wrote:

> Even a novice tennis player is capable of raising his hand accurately to meet the approaching ball although he may not be familiar with the laws of trajectile motion. Without any complex calculations of the velocity and position of the ball and racket, the player knows how to move his body to optimize the impact of his hand on the racket and ball, directing the ball towards a particular type of trajectile motion that will hit the other player's domain at a particular, pre-determined, point (p. 32).

The research studies by Host, Schonborn and Palmerius (2013) and Schonborn, Bivall and Tibell (2011), discussed in the earlier section also use the embodied cognition framework to analyze students' learning with virtual biomolecular model. The researchers, in both cases, use visuo-haptic simulations to study how tactile perceptions of virtual objects stimulate embodied knowledge and influence learning of abstract and sub-microscopic structures and interactions in students. While supporting their stance on the application of embodied cognition to the study, Host, Schonborn and Palmerius (2013) wrote "… the fact that the model actually allows the opportunity to feel virtual objects, such haptic perception could stimulate learners to integrate the offered sensorimotor experiences into their construction of the intended underlying scientific knowledge" (p. 3). Along similar lines, Schornborn, Bivall and Tibell (2011) wrote: "… experiencing a coordinated visual and tactile representation of biomolecular binding could have a potentially deep-seated influence on students' construction of knowledge concerning submicroscopic phenomena" (p. 2096).

Reiner (1999) used the embodied cognition framework in her study with tactile interface to explore the relationship "between embodied knowing and conceptual understanding in physics" (p. 32). The study was of the exploratory type. The author qualitatively analyzed data collected through 'think-alouds' and interviews from 12 graduate students with only high school physics background. The students constructed conceptual knowledge about fields from simulations. Reiner's simulations had very little visual content which helped the students focus more on the tactile feedback alone. The author observed that the students' representations of fields were very close to formal physics representations implying that the force feedback acted as the primary source for building these mental representations. Consistent with the idea of embodied theory, students used real life analogies to convey their conceptual understanding of the fields. The author appropriately concludes, "Tactile interface provides a gateway to tacit, non-propositional knowledge" (p. 53). Figure 2-3 below illustrates the author's belief in the influence of tactile interface on students' conceptualization of forces and fields through embodied cognition.

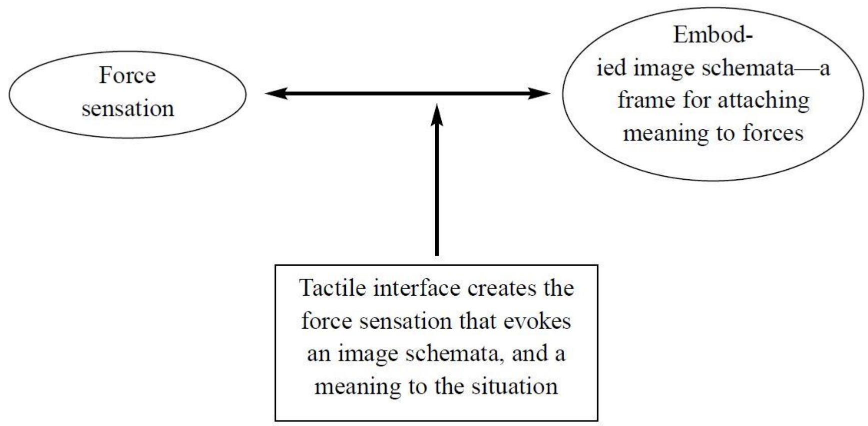


Figure 2-3. Tactile interface and embodied cognition, as per Reiner (1993)

This study also uses the embodied cognition as the underlying framework to explain the student perceptions of information in the haptic channel when they interact with visuo-haptic simulations. The embodied-cognition framework, and the prior studies discussed above, lay the groundwork for this study. The belief that the physical body's experiences and interactions with the surroundings influences and builds knowledge (Wilson, 2002), is integral to this research. This qualitative case study of student knowledge of electric fields gained through haptic simulations aspired to fill the gaps in the prior studies by analyzing how such "touch and feel" experiences influences student concepts and representations of these abstract and invisible electromagnetic concepts.

CHAPTER 3. METHODOLOGY

The purpose of this research study was to understand students' perceptions on using haptic simulations for learning electric field concepts. In this regard, this chapter details the methodology used for the study and the motivation behind the choices in depth.

3.1 Strategy of Inquiry

This research study was designed to be an exploratory case study to understand students' perception of the haptic feedback when they learn electromagnetic concepts with the help of haptic simulations. "The case study is a research strategy which focusses on understanding the dynamics present within single settings" (Eisenhardt, 1989, p.534). The premise of an exploratory case study, as discussed by Yin (1994), worked perfectly for this the study because the aim was to qualitatively explore students' perceptions and experiences while learning electric fields with the help of haptic simulations. The study followed a think-aloud protocol where the participants learned the electric field phenomenon through haptic simulations and talked about their experience. Reiner (1999) and Host, Schonborn and Palmerius (2013) have effectively used the case study approach in qualitatively analyzing student conceptual knowledge gain with haptics in force fields and nanoscience respectively.

3.2 Participants

Purposive sampling was the sampling method of choice for this qualitative study on students' perceptions with haptic simulations. Students from a Midwestern University were recruited with the help of flyers that were put up around campus. Students interested in the study filled out an online survey which was used primarily as a screening tool to purposefully choose the participants for the study. The survey included questions on students' background in Physics, their knowledge on the subject of electric fields and their experience with haptic technology. The content of the online survey is available in Appendix A. Nine undergraduate students were later chosen, from a pool of 12 volunteering students who filled out the survey, to participate in the final study based on their physics background. These students were selected because they had not completed any Physics course that dealt with electromagnetism at the University at the time of the study. Out of the nine participants, three were freshmen, four were sophomore, one was a junior and one was a senior at the Midwestern University. Two of them had not taken any Physics courses at the university yet. The rest of them had taken one or two general physics courses that dealt primarily with mechanics concepts and not with electromagnetism. Two out of the nine participants were females. Table 3-1 shows the participant's background and prior physics courses.

Table 3-1. Final study participant background

Participant ID	Gender	Year in University	Major	Electric fields background
S1	M	Sophomore	Computer and Information Technology	High school Physics
S2	M	Sophomore	Computer and Information Technology	High school physics
S3	M	Sophomore	Computer and Information Technology	High school physics
S4	M	Freshman	First year engineering	High school physics
S5	M	Freshman	Actuarial Science	High school physics
S6	F	Sophomore	Computer and Graphics Technology	High school physics
S7	F	Freshman	Electronics and Communication Engineering	AP physics - exam only
S8	M	Junior	Mechanical Engineering Technology	AP physics
S9	M	Senior	Computer and Graphics Technology	AP physics

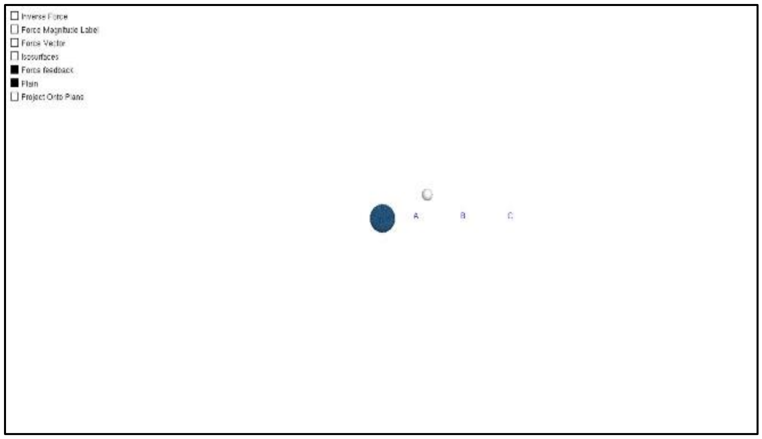
3.3 Data sources

Participants' responses on the pre-test used to assess baseline conceptual understanding, verbal data from interviews and think-alouds, audio-video recordings, participants' responses on the two progress assessment tests conducted during the data collection session, and field notes made by the observer were used as data sources for this study. The think-aloud protocol is most commonly used for studies exploring students reasoning with problem solving tasks, especially with simulations, since it elicits rich verbal data that informs the way they organize their thoughts during the task and also the cognitive processes that influence them (Ericsson & Simon, 1993; Fonteyn, Kuipers & Grobe, 1993). As the purpose of the study was to explore students' perceptions while learning with the help of haptic simulations, think-aloud protocol was used to encourage participants to verbally communicate their thought process while working on the simulations.

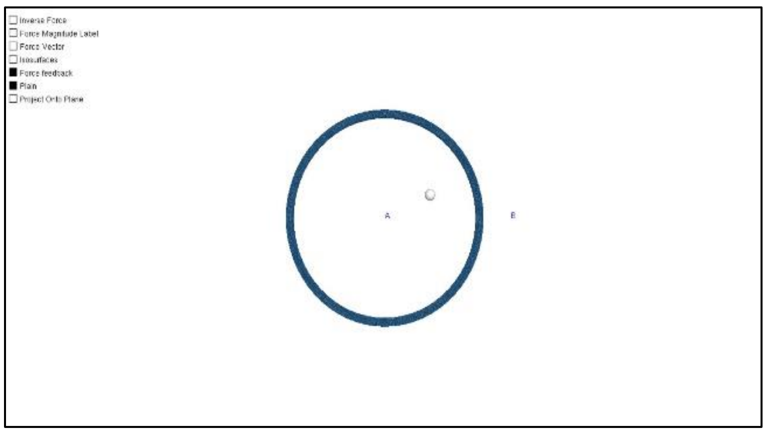
3.4 Data collection setting, materials and instruments

The data collection session was conducted with participants individually and at their convenience. On the day of the study, the participant met with the researcher either in a computer lab or a conference room in the university specifically reserved for the study. The labs and conference rooms used for data collection were not open to public during the time block reserved for the haptics study so that participants' identity could be kept confidential. The entire duration of the session per participant was less than two hours. The participant worked on the simulations on either the lab computer or researcher's personal laptop depending on whether the session took place in the lab or in the conference room respectively. In either case, a video camera was setup diagonally behind the participant in such a way that only the monitor was in focus, in order to maintain the confidentiality of the participant's identity. An audio recorder was also placed in front of the participant to record the think-aloud session. The audio and video recordings were primarily used for transcription and memory purposes. The participant was then briefed about the terms on the IRB approved consent form. The participants were made aware of the audio and video recording for the session before they signed the consent form.

The primary material used for this study consisted of visuo-haptic simulations of electric field around a point charge, line charge and ring charge. Each of these configurations involved a positive and a negative scenario. The simulations had checkboxes to switch the force feedback on and off. Checkboxes were also available to add and remove visualizations from the simulation, making it more modular, flexible and easy to use. The researcher worked on each of these scenarios with the students to understand their perception while learning the subject matter. Sample screenshots of these simulations for positive and negative charge scenarios are shown in Figure 3-1, and 3-2. Figure 3-3 is a blow-up of the options with checkboxes on the top-left corner of the screen in the simulations.



a



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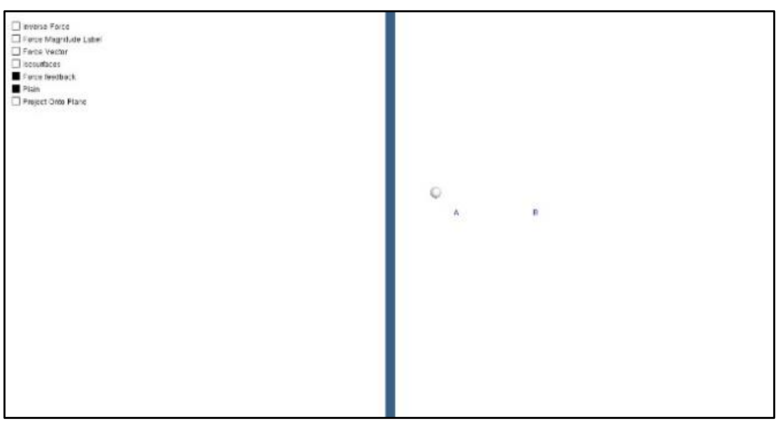
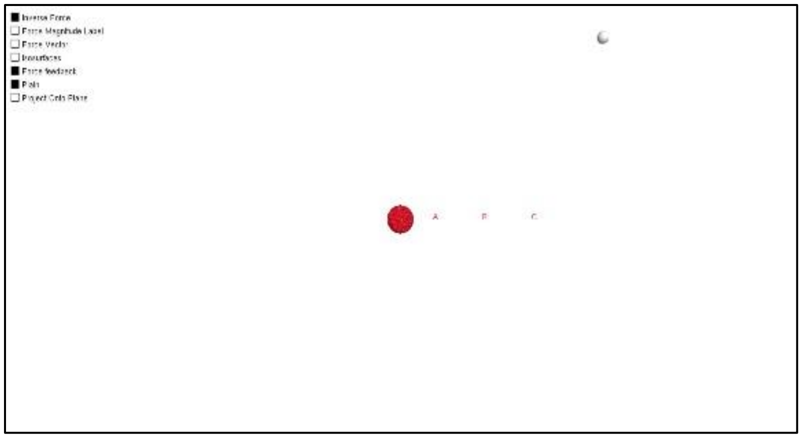
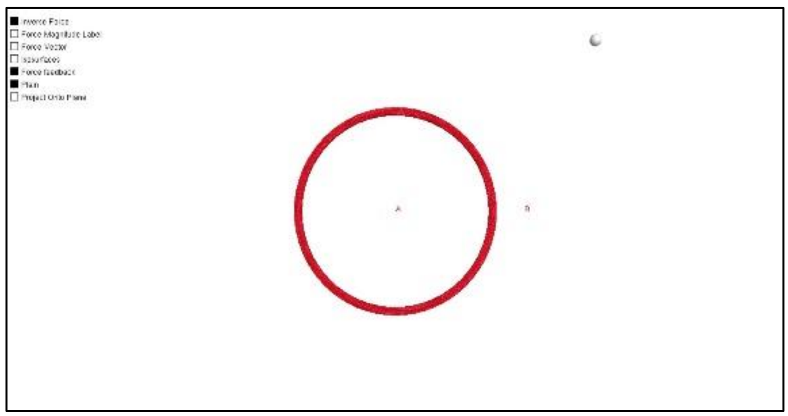


c

Figure 3-1. Screenshots of simulations for positive a) point charge, b) ring charge and c) line charge



a



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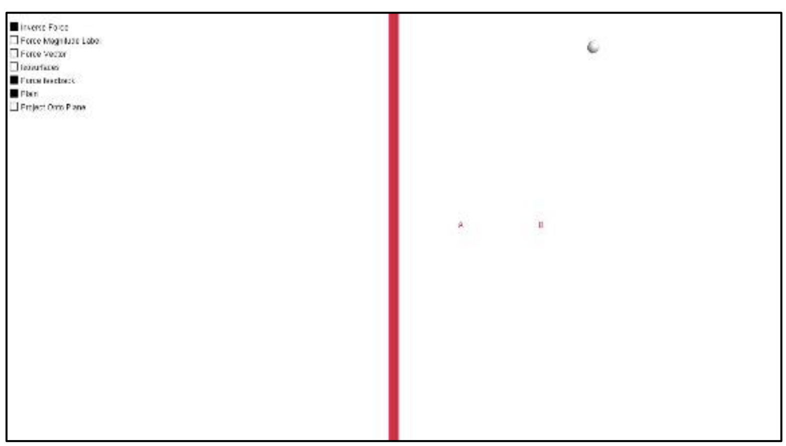
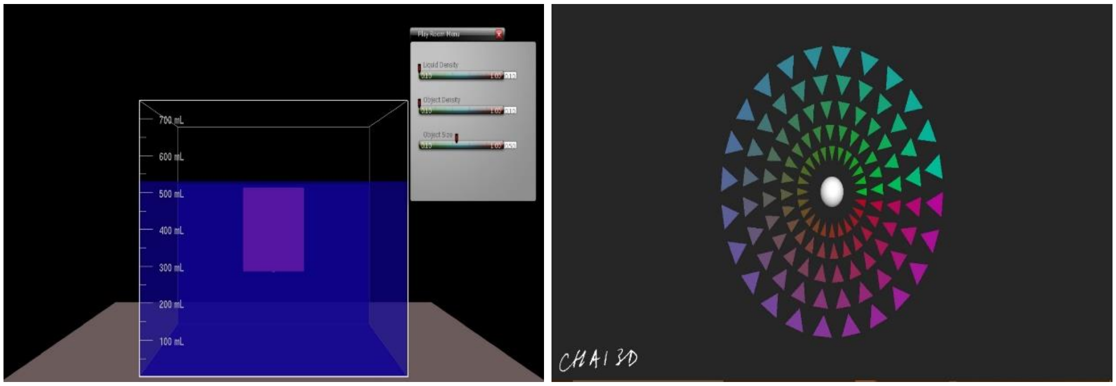


c

Figure 3-2. Screenshots of simulations for negative a) point charge, ring charge and c) line charge

Figure 3-3. Options available for each of the simulations - listed on the top left corner of the simulation window

Apart from the electric field simulations, sample CHAI3D (Conti, Barbagli, Balanuik, Halg, Lu, Morris, Sentis, Warren, Khatib, & Salisbury, 2003) simulations and buoyancy simulations were used as training material to give the students a brief introduction to visuo-haptic simulations and hands-on training with the haptic device. These are shown in Figure 3-4.



a b

Figure 3-4. Simulations used for training a) buoyancy, and b) CHAI 3D polygons

During their time in the session, the participants took one pre-test and two progress assessment tests. These tests were used to assess student's baseline knowledge and evaluate their progress while learning with haptic simulations respectively. The pre-test, shown in Appendix B, consisted of four open-ended questions. The two progress assessments were the same and had four questions each. The questions are listed in Appendix C.

The device used for the visuo-haptic simulations is the Novint Falcon (Novint Falcon, n.d). This affordable haptics device is used extensively in video games. The touch interface acts like a joystick and is used to manipulate objects on the screen. The force feedback on the touch interface provides the users a realistic experience while playing video games. A picture of the Novint Falcon controller is shown in Figure 3-5.

Figure 3-5. Falcon Novint haptic device

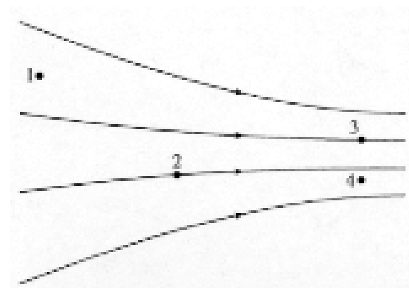
3.5 Data collection procedure for the final study

After the participants gave their consent by signing the consent form, they were asked to take the pre-test. The pre-test had four open-ended questions to assess the student's prior knowledge of electric fields. The questions used for the pre-test are listed in Appendix A of this document. Table 3-2 below lists the design steps. It also includes sample probes for the electric fields section. The students proceeded to work on the sample simulations once they completed their pre-test.

Table 3-2. Data collection procedure

Task type	Description	Sample questions
Pre-test	Four open-ended questions to assess conceptual knowledge on electric fields.	• What is an Electric field? How do we measure electric field at a given location in space? Give an example of another quantity that is a field.
Haptic introduction module	Introduction to haptic device and simulations	• Sample CHAI 3D simulation • Buoyancy simulation
Think-aloud	Audio and video recorded think-aloud session. Researcher uses a standard set pf probes to prompt the participants to think aloud during each phase.	<u>Questions for prediction phase</u> • What do you expect to feel? What do you predict the forces to be here? • How would the forces depend on the sign of the charge? <u>Questions for haptics phase</u> • Tell me what you feel? • Why do you think that is happening? • How does that feeling translate to your knowledge of electric fields?

Table 3-2 (continued)

Task Type	Description	Sample questions
Progress assessment test-I	Four objective type questions to evaluate learning at the end of the haptics phase.	• Rank the electric field strength in order from largest to smallest.  A. $E_1 < E_2 < E_3 = E_4$ B. $E_3 = E_4 < E_2 < E_1$ C. $E_2 = E_3 < E_4 < E_1$ D. $E_1 < E_4 < E_2 = E_3$ E. Not sure
Think-aloud	Audio and video recorded think-aloud session. Researcher uses a standard set pf probes to prompt the participants to think aloud during each phase. Probes at the end of the simulations for participants to reflect on their haptic experience in general.	<u>Questions for visual + haptics phase</u> • Has the visualization of arrows changed anything? How? • How did visualization affect your predictions from earlier phases? <u>Questions at the end</u> • Which simulations do you think conveyed better meaning for you: the one with visualizations or the one without? Why?
Progress assessment test-II	Four objective type questions to evaluate student's progress at the end of visual + haptics phase.	Same as progress assessment test-I

The students were first given a brief introduction to the haptic device and visuo-haptic simulations. They worked with sample CHAI 3D simulations and buoyancy simulations in order to get familiar with the haptic device and simulations. Once they felt comfortable using the haptic device, they moved to the visuo-haptic simulations on electric fields. At this point, the audio and video recordings were started and the participants were notified about the recording.

The electric fields module included the simulations for three configurations - point charge, ring charge and line charge. This module was recorded and the students were notified of that. This module was divided into three phases: a) prediction phase, b) haptics only phase, and c) visual + haptics phase and participants were introduced to the simulations in that order. During the prediction phase, the participants were presented with minimal visualizations for the positive scenario of the three configurations, as shown in Figure 3-1, and force feedback for the simulations was turned off. The participants were prompted to echo their predictions on electric fields around the point charge, ring charge and line charge. They were also asked to represent their predictions diagrammatically on a paper.

In the next phase, the haptics only phase, the visualizations were the same as in the prediction phase, but the force feedback was turned on. Students were again prompted to think and verbalize their thought process while working on each of three configurations. Participants worked with both positive and negative scenarios for each of the three configurations. Figure 3-1 and 3-2 shows the visuals for the positive and the negative scenarios. As in the earlier phase, they also represented their feeling of forces in each case on a sheet of paper. At the end of this phase, students took the progress assessment test-I (Appendix C). A sample question from progress assessment test-I is listed in table 3-1.

On completing progress assessment test-I, students were presented with additional visualization in the final visual + haptics phase, as shown in Figure 3-6. The students once again thought aloud and represented the electric fields for each of the charge configurations on paper. The additional visual cues included directional arrows for force, force magnitude and ISO surfaces. They worked with both the positive and negative scenarios in this phase as well.

The visual elements were diminished until this last phase on purpose. The research study aimed to explore students' perception specifically with information received in the haptic channel. It has been seen in the past that information perceived in the visual modal trumps the haptic channel when presented together (Srinivasan, Beauregard, & Brock, 1996). Reiner's (1999) experiences with students exploring force fields using the tactile interface in diminished visual environment also inspired this section of the study. Visual cues were removed for the haptics phase of the study in order to better understand how students perceive the learning experience and conceptualize electric fields purely with the haptic experiences.

However, the visual elements are important, and are integral for a holistic learning experience in 3-dimensional (3D) environments with haptic technologies. The combined multisensory environment provides a more naturalistic learning environment that would benefit the learning experience for students (Shams & Seitz, 2008). Visual cues were thus integrated into the final phase of the study, and student experiences and perceptions with haptic technology in the presence of visual cues were recorded again.

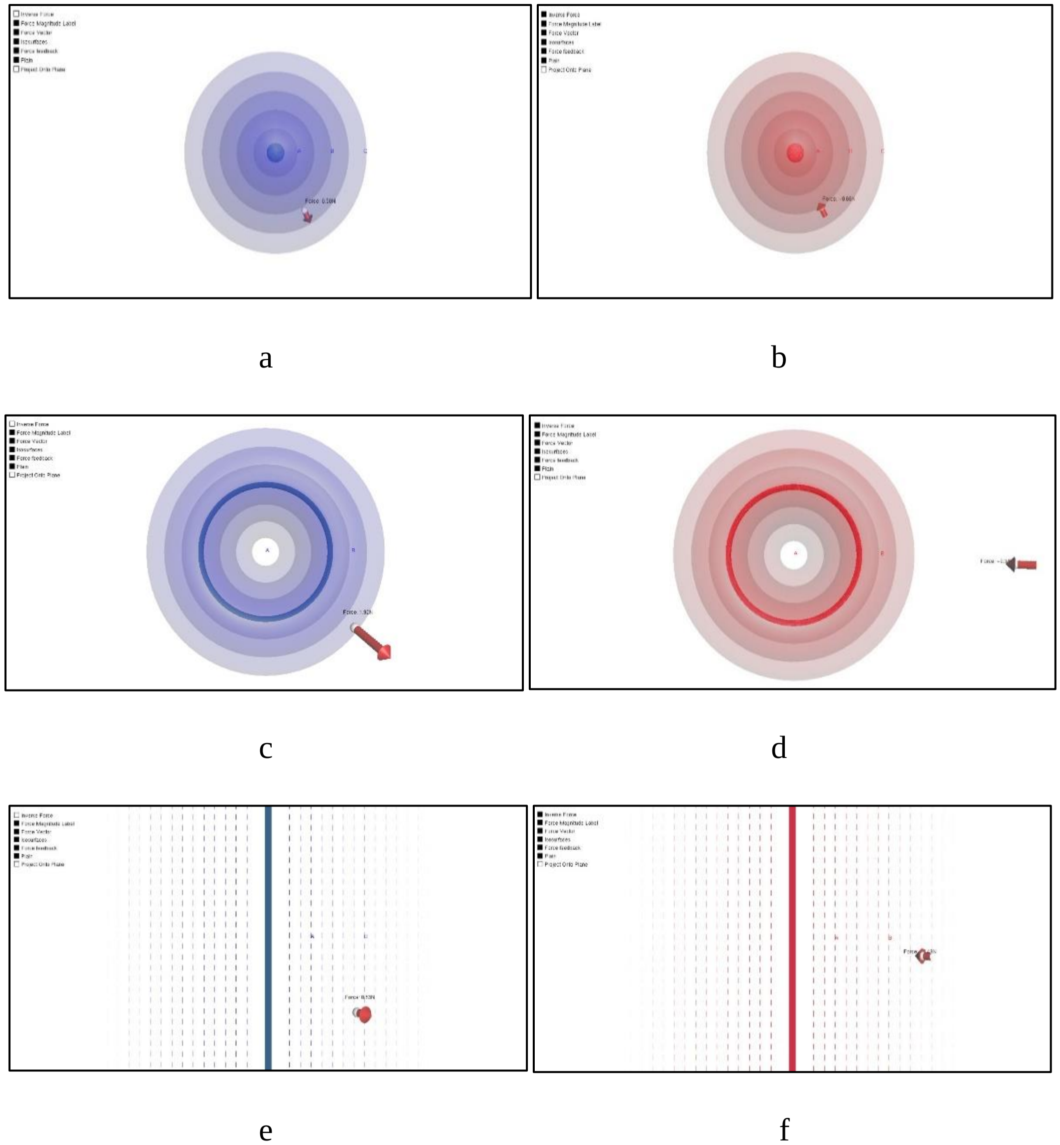


Figure 3-6. Screenshots for the visual + haptics phase of a) positive point charge, b) negative point charge, c) positive ring charge, d) negative ring charge, e) positive line charge and f) negative line charge

At the end of the visual + haptics session, the student takes progress assessment test-II, which contained exactly the same questions as in progress assessment test-I. The progress assessments were used to evaluate the progress made by the student at the end of each of the two phases with haptic simulations..

In each of these phases, the researcher asked a set of questions related to point charge, line charge and ring charge to aid the think-aloud process. These questions are listed in Appendix D.

3.6 Pilot study

A pilot study was conducted with five undergraduate participants which was used to inform the methodology for the current study. Table 3-3 summarizes pilot study participants' background

Table 3-3. Participants' background for pilot study

Paricipant ID	Gender	Year in University	Major	Electric fields background
PS1	F	Freshman	First year Engineering	AP physics
PS2	M	Freshman	Computer Science	High School Physics
PS3	F	Sophomore	Computer and Information Technology	High School Physics
PS4	M	Freshman	Materials Science Engineering	High school physics
PS5	M	Freshman	Chemical Engineering	AP Physics

The pilot study followed a think aloud protocol as well. The data sources included one pre-test, questionnaire with instructions, retrospective think-aloud and 1 post-test. The materials were similar except for the haptic simulations on electric field. The simulations at the time of the pilot study had only 2-d capability and did not include checkboxes to add visual cues and switch off force feedback. The visuals for these simulations were the same as Figure 3-1 and 3-2. In the procedure for the pilot study, the participants first signed the consent form and then worked on the haptic introduction module. Students worked on sample CHAI 3D simulations and buoyancy simulations (Figure 3-4) in this introduction module. After this, the participants jumped right into the electric field module. Students were given a questionnaire with instructions for the electric fields simulation for both positive and negative scenarios for the three charge configurations - point, line and ring charge. After completing each configuration, they were prompted to think aloud on their experience. Finally, in the end, participants filled out a post-test for the electric fields module. The materials for the pre-test and the post-test are available in Appendix E. The questionnaire for the electric fields module is included in Appendix F and the prompts for the think-aloud protocol are listed in Appendix G.

Pre-test and post-test results did not have significant differences or trends. The verbal reports were analyzed inductively for themes and patterns guided by the the theoretical framework of embodied cognition. The results from the pilot study and feedback from peers were used to inform the methodology of the final study discussed at length in this document.

While students used their embodied experiences of ‘push’ and ‘pull’ to conceptualize and represent forces, influence of prior knowledge in their conceptualization and representation of electric fields was seen throughout. In order to account for prior knowledge so that learning can be measured independently, an open ended pre-test and a prediction phase were included in the final study.

Some students came in with misconceptions about charges and electric fields and the haptics phase alone in the pilot study did not provide a holistic learning environment for them to correct their pre-conceptions. As a result, students' did not have a complete learning experience. The actual study included the visual cues in the final phase to provide the students with a complete learning experience with haptic simulations. Similarly, while the haptic provided the 3D capability, the simulations for the pilot study were designed for 2-d models. Changes were made to incorporate 3D simulations to maximize the learning experience with haptic and visuo-haptic simulations.

3.7 Trustworthiness

The materials used for the research study were reviewed and approved by experts and researchers in physics education and educational technologies. A pilot study was conducted with undergraduate students and methodology and results were discussed with experts and peers. Changes were made to incorporate their feedback. The questions used by the researcher during the interviews were reviewed iteratively by peers and researchers in education technologies to remove any researcher bias. Multiple data sources -– pre-test and progress assessment tests, verbal data from the think aloud sessions, and participants' diagrammatic representations – were used to analyze student perceptions and learning experiences with haptic simulations of electric field concepts, thereby ensuring Triangulation.

The participation was voluntary and the participants were be given a choice to refuse participation at every step. This was ensured to protect the participants' identity as well as to eliminate any threat to internal validity because of subject effect. The participants were screened to ensure all of them had similar physics backgrounds and none of them had participated in a haptics study before. The treatment was the same across all participants.

CHAPTER 4. DATA ANALYSIS

The purpose of the study was to explore undergraduate students' perceptions of haptic experiences while working with electric field simulations with 'embodied cognition' as the theoretical framework guiding the research. In this regard, the verbal data was first transcribed and an inductive analysis of individual participant data was performed. Categories and sub-categories were created for individual cases and then a cross-case analysis was also performed to identify patterns. Similar analysis was performed with students' diagrammatic representations of force-feeling and their assessments. While the pre-test provided the conceptual baseline for each case, the progress assessments were indicators of whether students were able to apply the knowledge gained through the simulations.

4.1 Baseline conceptual assessment

Students' responses to the open-ended questions in the pre-test were evaluated to assess their baseline knowledge of electric fields. All the students attempted answers for the definition of electric field, but none of them were right. An electric field is generally defined as a region around a charged particle where a force is exerted on other charged particles ($E = F/q$). Students' incorrect responses for electric field varied from "space surrounding an object where electric currents flow" (S2) to "an area where electrons are transferred" (S5) and "a field with magnetism and electric charge" (S9). However, some students did indicate magnetic field as an example of another quantity that is also a field.

While some students attempted to answer the questions on point, ring and line charges, most of them indicated ‘Not sure’ or ‘Don’t know’ as responses (marked by “-” in table 4-1.) None of the students who attempted a response were able to provide correct answers or draw representations for point and line charges. One student provided a partially correct answer for the ring charge. The rest of them were unable to explain or draw electric field for the ring charge as well. Results of the analysis of the pre-test for each participant is shown in Table 4-1.

Table 4-1. Analysis of participants’ responses on pre-test

Partici -pant	Electric Field	Point	Line	Ring	Overall
S1	Incorrect	Incorrect	Incorrect	partially right - a set of charge formed in a circular ring	0.5
S2	Incorrect	Incorrect	Incorrect	Incorrect	0
S3	Incorrect. But indicates example of electro-magnetic field	Unanswered	Unanswered	Unanswered	0.5
S4	Incorrect. But indicates example of magnetic field	Unanswered	Unanswered	Unanswered	0.5
S5	Incorrect. But indicates example of magnetic field.	Unanswered	Unanswered	Unanswered	0.5
S6	Incorrect	Incorrect	Incorrect	Incorrect	0
S7	Incorrect	Incorrect	Incorrect	Incorrect	0
S8	Incorrect. But indicates example of magnetic field	Unanswered	Unanswered	Unanswered	0.5
S9	Incorrect	Incorrect	Unanswered	Unanswered	0

4.2 Categorization of verbal data

Each participant's verbal data for each of the three configuration – Point, Ring and Line charge, was divided initially into three broad categories – Prediction, haptics and visuo-haptics – to align with their perceptions in each phase. The verbal data under each phase and configuration analyzed inductively with open-coding and sub categories emerged.

4.2.1 Prediction phase

For the prediction phase, student's verbal data for each of the three configurations were categorized into 'Concept', 'Force-distance relationship', 'Force-sign of charge relationship'. Students' initial response on what they think of the charge configuration in the prediction phase is categorized as concept. For e.g., participant S5's reaction below when he looks at the point charge simulation in the prediction phase is categorized under 'concept'.

> S5: "it's like a planet almost... it's an electron in some kind of field, and like A, B and C are maybe the radii of the electron cloud or something almost... I feel like an electric field would just be kind of a cloud."

When the participant talks about how the force at a point around the charge, the data is classified as Force-distance relationship. Similarly, participants' thoughts on the nature of the force and the sign of the charge is categorized as Force-sign relationship. For example, participant S4 predicts the 'force-distance relationship' as:

S4: "I would think that the closer you are to the point charge, the stronger the attractive force between that and the charge. And the farther out you go, the less of an attractive force it would be."

The participant's prediction on the nature of the force and the sign of the charge: "I'd say attractive force would be positive – negative", is classified as force-sign relationship. These categories were common across all three configurations. These categories in conjunction with pre-test results helped assess the baseline for students' knowledge on electric fields for point, ring and line charges.

4.2.2 Embodied experiences in haptics phase

Open coding of the verbal data for the haptics phase was heavily influenced by the theoretical framework of embodied cognition. This is because students talked about what they felt and how they perceived this feeling with electric field haptic simulations. A lot more categories emerged in this phase for each of the three configurations. Participants used embodied force experiences of 'pull' and 'push' to infer not just the sign of the source and probe charge, but also the shape of the force-field and force-distance relationship. Some participants used magnets as analogies to explain and conceptualize their feeling. While some categories were the same across the three configurations, some were unique for a particular configuration. These categories help answer the first part of the research question on "how students conceptualize embodied haptic experiences of electric field haptic simulations". Common categories across the three configuration, their definition and example participant data is listed below in Table 4-2.

Table 4-2. Categories for point, ring and line charge configuration in haptic phase

Category	Definition	Sample verbal data
Force Feeling	Participants' verbal report on what type of force they feel.	S1: "(positive) *it's, like, resistance. It's, you know, it's a pushback force. So it doesn't really want you to touch it. …* (negative) *It's definitely some sort of pull."*
Force-distance relationship	Participants' inference on the how the force changes with distance with respect to the source charge.	S3: "*there's definitely a lot of resistance to get it toward the point charge. And then at B-- so less and less. [...] I would say as you get farther away from the field you feel less resistance.*"
Sign inference	Participants' inference on sign of the source charge, assuming the probe is positively charged.	S5: "*I would say that one of the charges changed to an opposite charge and that's why it's getting sucked in, because the opposite charges attract each other. ...since the probe is positive that the center's now negative.*"
Shape of field	Inference on shape of the electric field around the source charge.	S4: "*in this case I'm feeling a cylinder around this line […] If I try to push through the line, so if I try to come towards me with how I have it sitting now it's pushes me around on either side, and so that tells me that there's this sort of ring shape in a single Z plane, if this direction is Z.*"
Indirect reference to electric potential concept	Participants use embodied experience to indirectly describe the work done to move the probe charge away or toward the source.	S2: "*the closer I get to this field the harder I basically have to push and if I get the probe here, it's like right next to the field and I just let go it immediately pushed away from it.*"
Analogy	Analogies used to relate to/ explain what is felt.	S8: "*These aren't two magnets pulling against each other, but they're creating the same type of force that magnets create when they're doing it.*"

One of the key observations in the participants' verbal report was the emergence of 'indirect reference to electric potential concept' category. Some students tried to explain what they felt by relating it to the amount of work done to move the probe toward or away from the source. For example, participant S8 described the experience for the positive charge in terms of effort as: "it's harder to go in than it is to come back out, and get further away from this center object". And for negative scenario, the participant describes the force feeling as: "The closer I get it's pulling my hand in and like I can't even control it. And it's really hard to pull out."

The categories listed in table 4-2 apply to both ring and line charges as well. However, a unique category for ring charge emerged from the verbal reports in the haptic phase. This category relates to the feeling of force at the center inside the ring, point A. The force at A is zero. However, in the haptics phase, participants do not see the force magnitude and so they talk about the force feeling or no force feeling at point A and they reason the presence or absence of the force. This category is explained with an example participant data in Table 4-3.

Table 4-3. Unique category for ring charge configuration

Category	Definition	Sample verbal data
Reasoning for force feeling at A	Participants' reasoning on why they feel or don't feel this force at A.	S8: "*It's not necessarily there's no force at A, it's just that all of the forces that are acting on A are equal and opposite in magnitude… Every single force that's acting on A cancels each other out … So anything that was already in A will tend to want to stay in A, because it's in equilibrium.*"

4.2.3 Challenges with haptics and misconceptions arising from them

Students faced some challenges and difficulties while working with the haptic simulations. These are categorized and listed in Table 4-4.

Table 4-4. Sub-categories in 'challenges' across all configurations in haptics phase

Category	Definition	Sample verbal data
Negative scenario	Students faced difficulty exploring the negative scenario because of the strong pulling motion and vibration of the haptics device.	S1: "*It's hard for me to grasp physically what's going on in this situation... Just because of like it's kind of the feedback, it's going to throw me off.*"
Depth perception	Students fail to see the 3D field in the haptics phase.	S1: "*So you don't know what's deep-- and it's hard with the white ball and the white background, because it's harder to recognize that at first. I didn't even know until now that it was getting smaller.*"
Device mechanics	Device limitations (hardware and software) that causes participants to misinterpret concepts.	S7: "*Even though there is no force, I can't move inside the circle very consistently... The joints are not very flexible, I guess.*"

The negative scenario for the configurations was implemented with a 'pulling' force. When the probe is moved closer to the source charge, a 'pulling force' is experienced by the user. When the probe is released, it is pulled into the source with a force. However, it overshoots the source because of the force and results in a vibrating motion because of the correcting force effect that ensues. This vibration was loud and distracting for the participants. Four participants tried to incorrectly conceptualize the vibrating motion of the probe charge around the source charge for the ring and line configurations. Participant S2 attributed the vibration to the attraction of the probe charge to other points on the ring charge

> S2: “As I get closer to the line, it's not just sticking to one point and being there and being all happy because the opposites are attracting. It's being attracted to just many, many, many points along here. So, it kind of just jittered back and forth between them, which is why it's doing that.”

Participant S5 thought he felt the probe charge orbiting around the source charge. “it's just like crazy forces going in each direction. That's why it's jumping so much. And it just wants to keep it-- it felt like it was almost orbiting, almost going around in a circle.” Similar observations were made by two other participants for line configuration as seen below.

> S3: “I guess the probe-- when it gets near it, it kinda bounces off. It’s looking like it’s trying to escape, kind of, from the field, but then it gets pulled back in, and then that kinda makes it... rotate around”
>
> S8: “…with the way this thing is going it’s not staying directly on the line, because once you’re here there’s forces, like, in this area that are pushing it in towards their center but from the other way. And so it’s going to create this natural tendency to do this tiny little orbit around the point…”

The other major challenge with the haptic simulation was the perception of depth in the visual model. The haptic device provided the 3D capability. However, the visual images of point, ring and line charges used in the haptics phase was very 2-dimensional. The only way to understand the position of the probe along the outward plane was to notice the change in the size of the probe charge when moved in and out of the plane. As a result, participants had to be constantly reminded to push the probe in and out and feel the force at different planes. Figure 4-1 shows the apparent position of the probe along the outward plane for the three configurations.

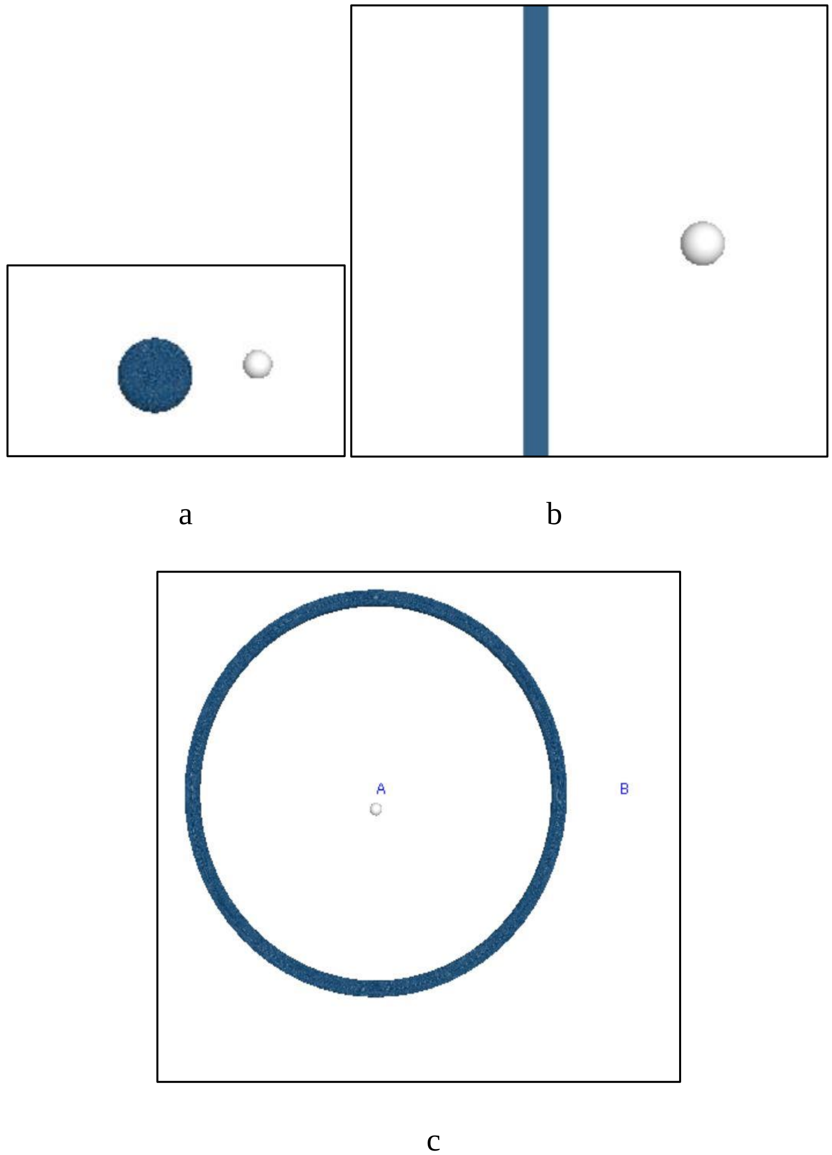


Figure 4-1. 3D perspective - Screenshots of point, line and ring charge showing the position of the probe charge a) above the plane, b) along the same plane, and c) below the plane of the source charge.

Two of the participants also faced challenges perceiving forces because of the device’s mechanics. They mistook the inherent stiffness of the device’s arms to a force feeling. Participant S1 perceived it to be a repulsive force feeling away from the source charge: “I don’t really feel a force of attraction, but I feel a force of, like, repulsion as you get further away.” Participant S5 talked about force feeling when the force feedback was switched off. When asked about that, participant S5 complained about the stiffness of the haptic arm during the ring charge configuration: “Oh, that’s weird. Because the force is not consistent. Even though there is no force, I can’t move inside the circle very consistently... The joints are not very flexible, I guess.”

4.2.4 Visual + haptics phase

In the final visual + haptics phase, participants used the visual cues along-with the haptics information to confirm and reinforce their learning from the haptics phase. Participants compared their learning experiences in the haptics phase and the visual + haptics phase and talked about how elements in each phase influenced their understanding of the concept. For the final visual + haptics phase, the verbal data for all the three configurations – point, ring and line charge were coded together. The emergent categories are explained with sample data in table 4-5.

Table 4-5. Categories in the visual + haptics phase

Category	Definition	Sample verbal data
Visual + haptics reinforce/cements/ makes learning concrete	Students felt that the final phase with both visual and haptics reinforced learning and ‘cemented’ concepts	S5: “*I think it would make the learning process much easier and much more concrete. They'll be able to understand what they're learning, and what's actually going on on paper. They'll be able to understand that much better, just because they could actually feel and see it.*”

Table 4-5. (continued)

Category	Definition	Sample verbal data
Visual cues clarify	Participants felt that the visual cues in the final phase helped clarify the concepts	S8: "*You know how I was saying with the ring and how it was kind of hard to determine the actual direction of where your force is going to be since you've got so many forces acting on it in so many different directions. Yeah, this gives you a really clear idea of where whatever was at A is going to go due to the action of these forces.*"
Visuals for depth perception	Participants believe that visual cues help perceive the depth in 3D haptic simulations of electric fields better.	S4: "*It also provides a plane so you can see where you are.*"
Visuals for force magnitude	Participants believe that visual cues help relate to the strength of force.	S5: "*with the ring now it's easy to see that at the center there's no force, it even says, 'No newtons' and there's no arrow.*"
Visuals to see continuous field	Visual cues helps participants in seeing that the field is continuous and fades off in the distance rather than have a distinct boundary.	S6: "(visual cues) *helps me kind of understand better that there are still forces, even though you can't feel it or anything like that. Like I said, I didn't feel it in B, I don't think, so just the fact that I can see this arrow and it shows me exactly how much force is acting upon a certain area is just super helpful.*"
Haptics to relate to force magnitude	In conjunction with visual force magnitude cues, participants believe haptics help understand what that amount of force feels like.	S2: "*…the force feedback really cements how it feels, because if I'm trying to just do this, like sure, it's telling me that this is 42 newtons. And that's great, but I don't know how that feels, I don't know how relatively strong that is. But with the force feedback I'm able to tell that like, it's pretty difficult to get to this point and keep it here, because all it wants to do is push me away at 50 newtons. And so it's a far better learning experience using the feedback instead of just the visual.*"

Table 4-5. (continued)

Category	Definition	Sample verbal data
Haptics for 3D modelling	Haptics help perceive 3D simulations better	S9: "*I don't know that the visual was particularly helpful in the three-dimensional sense. In the Z axis the visual arrows were just a little bit too difficult to decipher… the haptic feedback was definitely the most powerful element in that.*"
Haptics for memory retention	Haptic modality helps remember these concepts.	S6: "*the feeling, I feel, is a really important part of learning. I think it adds that extra kind of-- not motivation but experience or something that kind of helps information stick.*"
Haptics experience for motivation	Haptic experience motivates learning	S3: "*if I was just trying to learn about it, you could get bored pretty easily. But this got me physically involved. It got me active and, yeah, I was able to stay involved with it the whole time.*"
Learning curve for haptics	Students talk about a learning curve for haptics	S1: "… it's the learning curve... it probably took me a full hour to fully get what's going on and how to use it exactly and feel it properly and get adjusted to the equipment."

Some participants talked about challenges with visualization in the visual + haptics phase. These reports are classified under the challenges category created in the haptics phase. One of the participant had troubles relating to the visualization for the line charge.

> S7: "I don't know if it's only picture I would be super confused...Because I don't know what this line represents, like why there is space between each line. It's like segment, segment so I don't know which direction…"

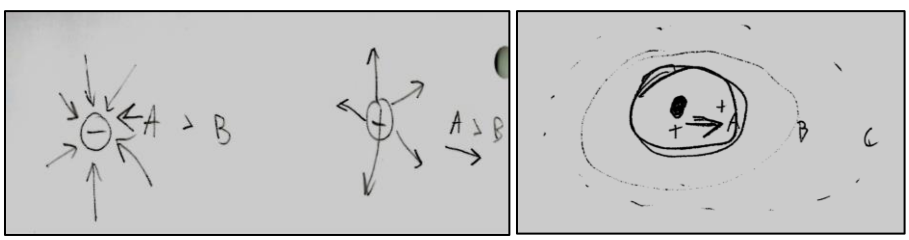
Another participant S8 mentioned about jumps in arrows for the visualization. : "Well, it looked like there are a couple of jumps where just at a certain runtime it's not finding the same feedback at different points, and that just could be because of… probably the coding equation."

Participant S9 also talked about visuals misleading his perception.

> S9: “The arrow does get much larger, but it's a very great distance so maybe, I don't know, changing the perspective to be a little bit wider would help kind of give you the depth perception, but aside from that the torus surface is clearly an inaccurate representation of the actual force.”

4.3 Representation of force-feeling

The second part of the research question is to understand haptics’ influence on student representations of electric fields and forces. In order to answer this, participants’ diagrammatic representations of force-feeling were analyzed per configuration and across the three phases to see how representations evolved based on embodied learning. Figure 4-2 shows snapshots of correct representation by participants. An incorrect representation is shown in Figure 4-3.



a b

Figure 4-2. Correct representations of forces around a point charge by a) S1 in visual + haptics phase and b) S2 in prediction phase

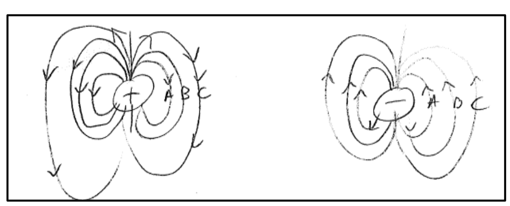


Figure 4-3. Incorrect representation of electric field around a point charge by S1 in prediction phase

Similarly, correct and complete representations for ring and line charge configurations from students' reports are shown in Figure 4-4 and Figure 4-5 respectively.

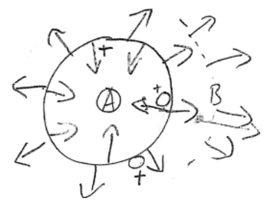


Figure 4-4. Correct representation of Ring charge by participant S2 in haptics phase

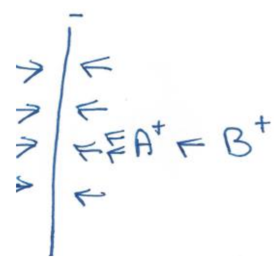


Figure 4-5. Correct representation of forces around a line charge by participant S3 in haptics phase

Examples of incomplete representations are also shown in Figure 4-6. Even though the participant (S4) represents the force direction corresponding to the sign of the source charge, and also represents a decreasing force from points A to B by showing variable sized force arrows, the participant fails to represent forces on both sides of the plane and/or the parallel nature of the field. This kind of representations were classified as incomplete.

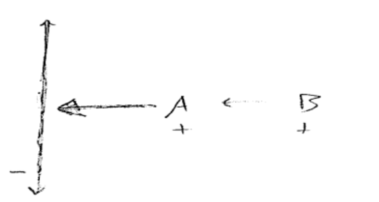


Figure 4-6. An incomplete representation of a line charge by participant S4

It was observed that some participants also attempted to represent force-feeling in a 3D manner. Sample 3D representations for a ring and line charge by participants S9 and S2 are shown in Figure 4-7. This observation was compared with verbal data to see at what stage participants make the 3D inference during the entire process for each configuration.

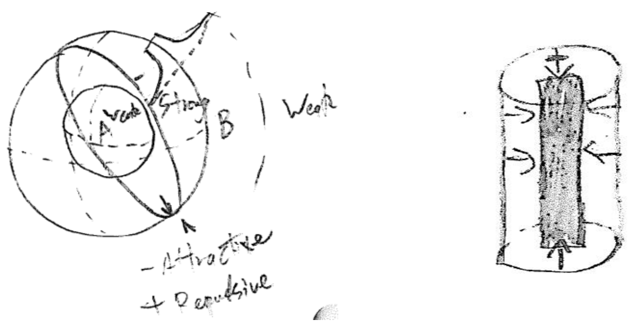
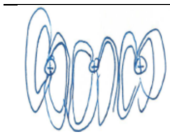
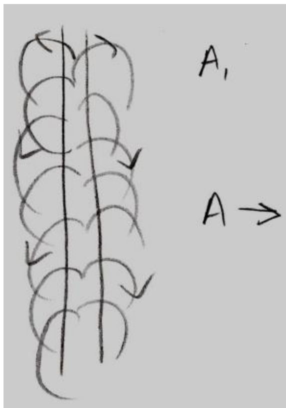
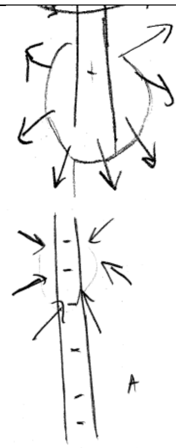
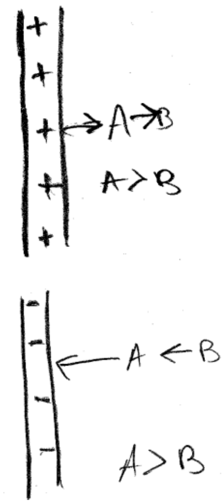


Figure 4-7. 3D representations for ring and line charge by participants S9 and S2 respectively

Within each configuration, the representations were compared across pre-test (if any), and the three phases – prediction, haptic and visual + haptics phase, to observe how representations evolve. Participants' diagrammatic representations were also compared with their verbal reports from each phase for congruency. An example analysis of the representation for a line charge is shown in Table 4-6.

Table 4-6. Example analysis of student representations (S1) of electric field for a line charge across pre-test, prediction, haptic and visual + haptics phase

Pre-test	Prediction phase	Haptics phase	Visual + haptics phase
 Incorrect representation ["*I'm assuming it's a ring of charges.*"]	 Incorrect representation with arrows going from one side of the line to another is wrong. But talks about parallel nature of forces and Force at A being greater than that at B. ["... *parallel to the line, it would be, as long as you're the same distance, a parallel line, it would be consistent*"]	 Correct representation. Mentions A>B on paper. Spherical/cylindrical (3D) influence in representation. [*"this feels more like a tubular structure, which is what I would probably imagine ."]*	 Very 2-d representation. very confirmatory from the way he talks ["*I mean it looks like it's staying the same.... (along a parallel line*)"]

As can be seen in the example, the representation evolves from an incorrect representation in the pre-test and prediction phase to a correct and more formal representation in the haptics phase. The student (S1) also attempts a 3D representation of forces around the line charge in the haptics phase. Supporting verbal data is also shown in the table for each phase. Similar analysis was performed for point and ring charge. Examples of these are shown in Table 4-7 and Table 4-8 respectively.

Table 4-7. Example analysis of student representation (S6) for a point charge across pre-test and the three phases – prediction, haptics and visual + haptics

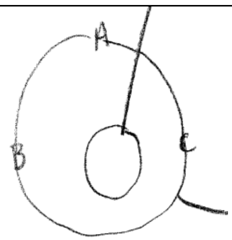
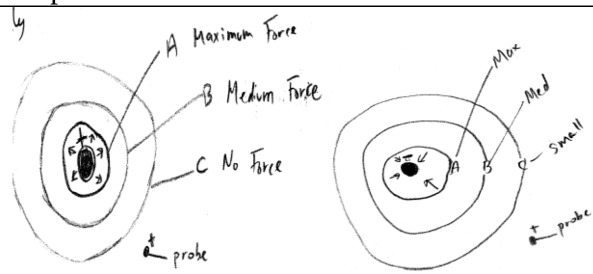
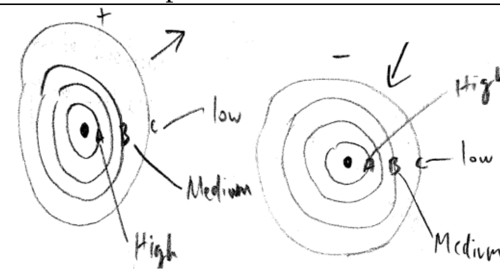
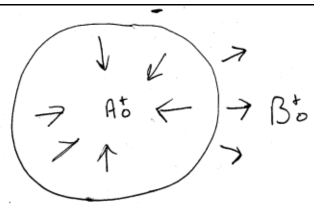
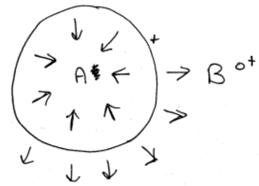
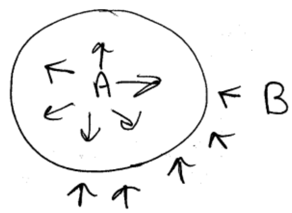
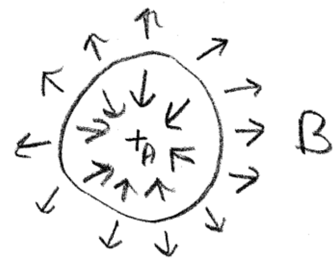
Pre-test	Prediction	Haptics	Visual + haptics
No field representation. Incorrect. [“*A point is electric energy given off in a single point*”]	 Incorrect representation of field around point charge. Participant draws an uneven ring around to depict the field, but marks all the points on the same ring. However mentions stronger force at A [*stronger force at A, and then as you go out.. you can feel it a little less*] No direction, no sign inference.	 Good representation, with arrows, rings and charge sign. No 3D shape reference. Talks about 2D circle [“*since it’s, like, a point it would, like, the electric field would kind of go out in like a circle.”*] Participant unsure about the sign of the charges initially. Identifies incorrectly in both positive and negative at first. Corrects after a lot of thinking and revisiting the magnet analogy. [“*That would be positive-negative, right? Or would that be positive-positive? Now I’m confusing myself…. positive*-positive.*”*] when the researcher mentions that the probe is positive [“*I’m going to assume it would be negative then maybe... I kind of want to, I really do want to change this to positive-positive. Just because in terms of magnets I feel like since both, if it’s the same end on both magnets and you’re trying to put it together, then they-- it just doesn’t work.”*]	 Very similar to haptics. [“*kind of solidifies my answer”*]More rings. Good representation. Mentions ‘low force’ at C. 3D reference [*There’s a force basically acting on all sides, all around this point*] continuous nature of the field [*helps me kind of understand better that there are still forces, even though you can’t feel it or anything like that. Like I said, I didn’t feel it in B, I don’t think, so just the fact that I can see this arrow and it shows me exactly how much force is acting upon a certain area is just super helpful*.]

Table 4-8. Example analysis of participant S3's representation of electric fields for a ring charge across pre-test and the three phases

Pre-test	**Prediction**	**haptics**	**Visual + haptics**
'Not sure'	 Incorrect representation. Forces inside and outside the ring are represented correctly. But direction is reversed. Participant is able to predict that probe would want to stay at A. ["... *the probe's going to want to stay right here. Yeah, at A."]* Doubts the possibility of an 'attractive force' ["*it makes more sense to me that they would be opposite forces. So it would be pushing it away, I guess… I'm not sure when it would be attracting. I guess I'm thinking it's always going to be resisting the blue-- the circle... I'd say it'd still be the negative and positive scenario.*"]	  Good 2D representations of forces inside and outside the ring. Note the directions are corrected. Participant talks about spherical shape of the field and feeling of 'no force' at A. ["*I don't feel anything at A, but if I try to move out, it's a little tiny sphere inside of balance with no charge*"] reasons out why there is a 'neutral zone' at A["t*here's a balance right there, because everything's going toward the middle, so everything's kinda evening out*"]	 No change in representation from haptic phase. However, Student notes that visual elements make the learning more concrete. Student had difficulties with negative scenario with haptics alone. Visual helped clarify. ["*I kept thinking there was something right here that I was being attracted to, but with the arrow on it will see now, that it's definitely the ring and not something on the inside."]*

4.4 Assessments

Students' progress assessments were evaluated to see the progress made at the end of the haptics phase, and again at the end of the visual + haptics phase. Results per participant is shown in Table 4-9. These responses were only evaluated to assess participants' progress after the haptics phase and the visual + haptics phase. A thorough quantitative analysis is beyond the scope of this study. No specific patterns or trends were observed in students' responses between the progress assessment tests I and II (PA1 and PA2 respectively). All but one participant either scored the same or slightly better on PA2 when compared to PA1.

Table 4-9. Analysis of participants' progress assessments

Participant ID	PA1	PA2	Notes
S1	2	3	corrects response for Q3-line charge on PA2; incorrect response for field ranking in PA1 and PA2
S2	4	4	
S3	3.66	3.66	Indicates non-uniform forces, but reasoning is incorrect
S4	2.66	3	Did not indicate non-uniform charges in PA1
S5	4	4	
S6	3.66	3.66	Did not indicate non-uniform charges
S7	2.33	1.33	Incorrect representation for ring charge; only non-uniform forces indicated in Q1; ranking Q2 wrong in PA2
S8	3.5	4	incorrect reasoning for Q3 on line charge in PA1
S9	3.33	3.33	only non-uniform forces indicated as incorrect

CHAPTER 5. RESULTS AND DISCUSSION

This study aimed to explore undergraduate students' perceptions about learning electric fields using haptic simulations, specifically:

- How do they conceptualize haptic experiences of electric field simulations?
- How do the haptic simulations influence students' representations of electric fields and forces?
- What are their perceptions on experiences with both haptic and visuo-haptic simulations of electric field concepts?

The data analysis discussed in the previous section was carried out with these questions in mind. This section will discuss the findings from the analysis to answer the research questions in the same order.

5.1 Conceptualization of electric fields with haptic simulations

The first part of the research question aimed to understand "how students conceptualized haptic experiences of electric field concepts". It was seen that students translated the 'feel' with haptic simulations to 'concepts' relating to electric field. The 'force feeling' category in the haptic phase includes participants' verbal report on how they verbalized the feel of forces and what it meant in terms of electric field. Students used a combination of the following words across the three configurations of point, ring and line charges to describe the type of force felt between like charges.

> “Pushback force”, “resistance”, “pressure”, “repelling/repulsive force”, “Pushing away”, “deflection”, “Invisible shield not letting me go”, “can’t get close/touch”, “hard to push in”, “force against my palm”, “move away”

Similarly, to describe the force between unlike charges, participants used a combination of the following words.

> “Pull”, “sucking in”, “attracted”, “drawn”, “shoved”

Because of the ‘vibrating’ nature of this force, students also used “vibration”, and “out of control” to describe this force.

Participants for the study were chosen based on their physics background. None of the participants had completed any course on electric fields and electromagnetism at the University at the time when this study was conducted. All of the nine participants scored poorly on the pre-test given to assess their conceptual understanding of electric field concepts, specifically with point, line and ring charge configurations. In the prediction phase however, just by looking at the minimal visuals of the charge configurations, students recollected and applied basic high school physics concepts of inverse force – distance relationship (as distance increases, force decreases). Two of the nine students, S4 and S7, even noted the 1/r^2 relationship for force–distance relationship. The inverse squared relationship holds true only for the point charge scenario. S4 incorrectly noted this relationship during the line charge configuration in the haptics phase, but mentioned that he knew this from physics lecture. S7 mentioned about the relationship during the point charge configuration in the prediction phase. Irrespective of the knowledge of the formal force-distance relationship, all participants who noted an approximate inverse relationship for each configuration are considered for this analysis on conceptual baseline. The graphs in Figure 5-1 show the number of students who predicted an inverse force-distance relationship correctly in the prediction phase for each of the configurations.

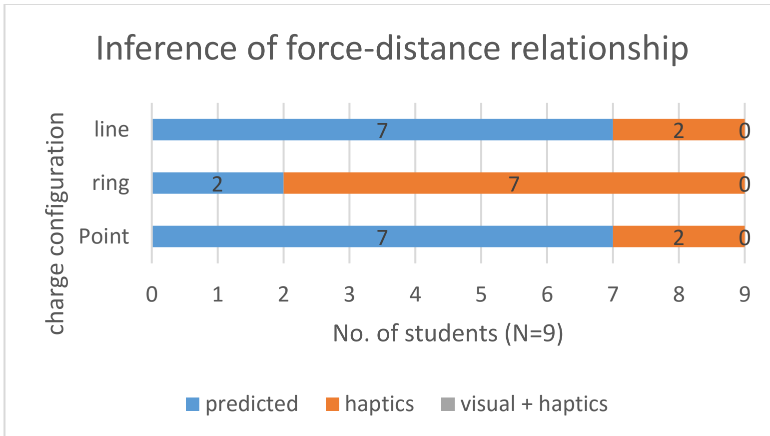


Figure 5-1. Graph to show the inference of force-distance relationship at different phases in the study

Out of the nine students, seven predicted the force-distance relationship correctly in point charge and line charge in the prediction phase while the two other students gained that knowledge in the haptics phase. Out of the seven who predicted the force-distance relationship, two of them had taken AP physics exams in the past (S7 and S8). However, for the ring charge configuration, only two of the nine participants predicted the force distance relationship correctly (S2 and S3) and the rest gained the knowledge in the haptics phase. The two participants with correct force-distance relationship had not completed AP physics and had basic electric fields knowledge from high school physics lectures.

All of the nine participants also used analogies to translate the tactile force feeling to a concept. Eight of the nine participants used magnets as analogy to conceptualize and infer the force-sign relationship. For example: S6: “I feel like, it almost feels like a magnet. Just like the amount of, like, that pressure you feel. When you try to, like, stick it to the other one.” One participant used music analogy to translate the feeling of increasing force as the probe moves into the source charge.

With haptic being the primary modality, students were also able to infer the shape of the force field in 3D. The haptic phase had absolutely no visual cues to suggest a spherical (in 3D) or a circular (in 2D) field around point and a ring charge and a cylindrical (in 3D) field or a wall (in 2D) around the line charge. However, as shown in the graph in Figure 5-2, out of the nine participants, six, eight and eight of them were able to infer the shape of the field for point, ring and line charge configurations respectively, purely based on information from the haptic feedback in the haptics phase. Cumulatively considering both the haptics phases –haptics and visual + haptics phases, it can be seen that eight out of nine students had 3D inferences in their verbal reports for point and ring charge and all of them had 3D inferences for line charge after working with haptic simulations.

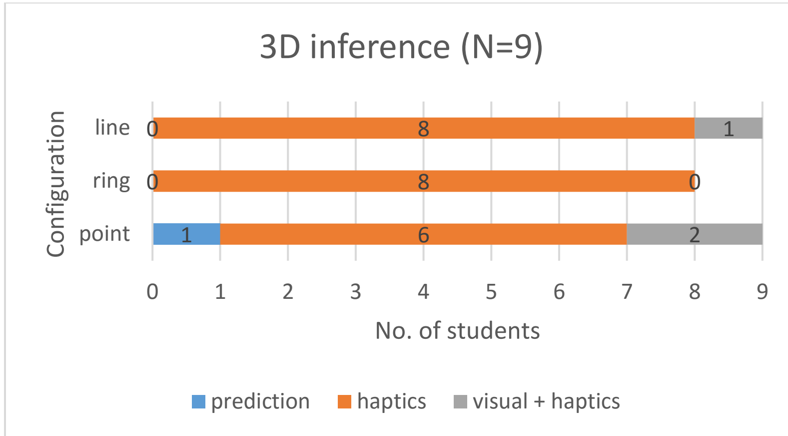


Figure 5-2. Graph to show haptic influence on 3D inference of the electric field for the three configurations

Another observation from the embodied experiences in the haptic phase was participants' reasoning for why they wouldn't feel forces at the center inside the ring. In this case, participants used the embodied information in the tactile interface as a tool for reasoning. As seen in the graph in Figure 5-3, four out of the seven students who reasoned correctly used the haptic experience during the ring charge configuration to reason as to why the force at the center inside the ring is zero. Two of the seven students had correct reasoning for zero force at the center within the ring in the visual + haptics phase. Overall, six of the nine students were able to reason zero force at the center inside the ring after experiencing the haptic/visual + haptic simulations.

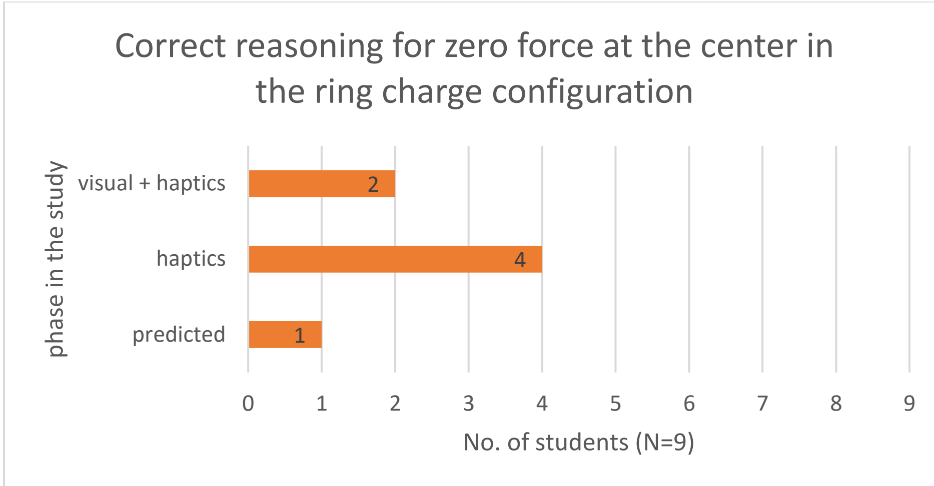


Figure 5-3. Graph for students' correct reasoning for zero force at the center inside the ring charge configuration.

5.2 Representation of electric fields and forces

The second part of the research questions was to understand "how the haptic simulations influence students' representations of electric fields and forces". To answer this question students' representations of fields from pre-test (if any) and force-feeling from each of three phases – prediction, haptics and visual + haptics phase were compared to see how their representations evolved. A comprehensive analysis with all students' representations of force-feeling, along-with their verbal reports, was done for this discussion.

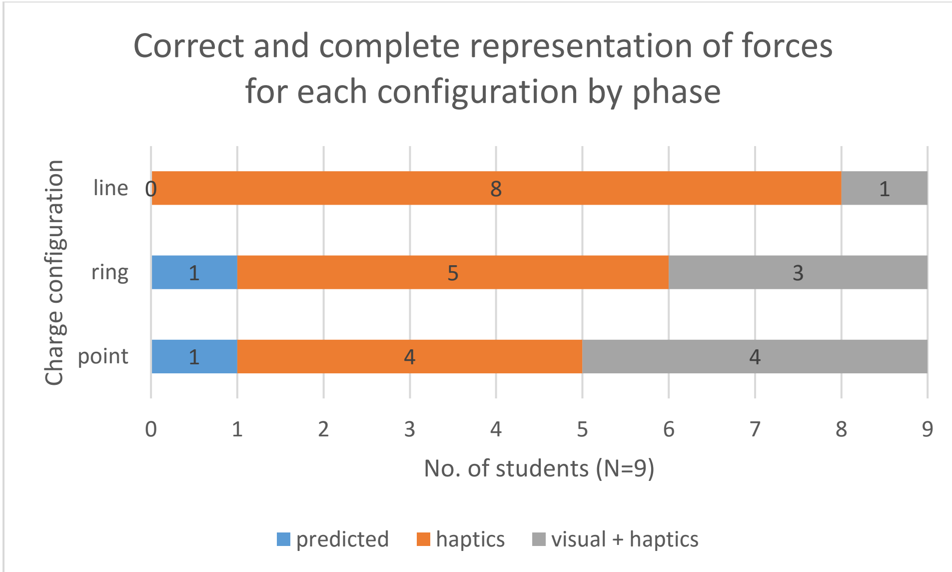


Figure 5-4. Evolution of representation of force-feeling for each configuration by phase for each charge configuration

Figure 5-4 shows a graph showing the evolution of participants' representations of force-feeling for each configuration across the phases. It was seen that overall, haptic simulations had a positive influence on students' representation of forces, especially for ring and line charge configurations. Accumulating the learning in haptics and visual + haptics phase, eight, eight and nine participants' representations of force-feeling evolved for point, ring and line charges respectively. For point charge configuration, one out of the nine students had the correct and complete representation in the prediction phase (S2). Out of the remaining students, four of them had a correct representation in haptics phase (S3, S6, S8 and S9) and four got it right in the final visual + haptics phase. In the ring charge configuration, only one of the participants (S2) had a complete and correct representation in the prediction phase. Five participants were able to represent forces around a ring charge correctly in the haptics phase (S4, S6, S7, S8 and S9), while three got it complete and correct in the final visual + haptics phase. For the line charge configuration, none of them had a complete representation in the prediction phase. But in the haptics phase, eight of the nine students had a complete and correct representation of forces around a line charge and the one remaining student had an evolved representation in the final visual + haptics phase (S8). Looking at representations cumulatively across the haptics and visual + haptics phases for the three configurations, it is clearly evident that students used embodied learning experiences to represent their conceptual understanding of electric field and forces, especially in the case of line and ring charges. Reiner (1999) also found similar results with graduate students with little physics background. Her study showed that haptic experiences promote learning by evoking tacit and non-propositional knowledge. On the matter of students' experiences with forces for field representations she noted:

> Fields are often represented through mathematical formulation or graphical representation only. Sensory experience of field forces in the lab is often impossible, due to low magnitude of the forces. Thus the sensation of force is rarely involved in the construction of the concepts of field (p. 33)

The experience of sensing realistic forces was evident in the way students marked the forces at different points and talked about the varying 'feeling' of forces at these points.

Another major influence of the haptic simulations was observed in participants' 3D representations of force-feeling. Not all students attempted representing in 3D. The graph in Figure 5-5 shows the number for the first instance of 3D representation of force-field by participants for point, line and ring charge configurations. In the haptics phase, one out of the nine participants attempted a 3D representation for point charge, while another student had a 3D representation in visual + haptics phase, and five out of nine had 3D representations for ring charge. For the line charge configuration, five out of nine tried 3D representation in the haptics phase while one out of the remaining four had a 3D representation of force-feeling in the visual + haptics phase. Participants S4 and S7 consistently had 3D representations in all three configurations – point, ring and line. Participants S2 and S5 had 3D representations for both line and ring charge configurations in the haptics phase. The other participants with 3D representations in either ring or line charge were S9 and S1 respectively. S8 had a 3D representation of the line charge in the visual + haptics phase. It is important to note that none of the students had a 3D representation to start with in the prediction phase, but in the end seven of the nine participants had 3D representations in at least one of the configurations.

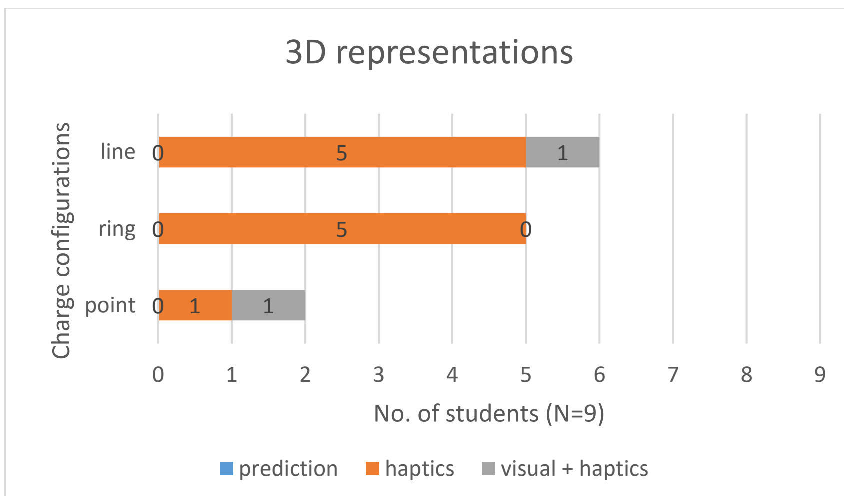


Figure 5-5. First instance of 3D representation of electric field by students for the three configurations across the three phases.

It must also be noted that the discussion on 3D representations is exclusive of the 3D inference by students which was discussed in the previous section on conceptualization (Figure 5-2). Not all students who inferred 3D shape of the field represented them in 3D format. However, the converse is true. All students who had 3D representations inferred 3D shape.

From these results discussed in this section, it can be seen that haptics had a positive influence on students' representation of electric fields and forces in general and also motivated students to incorporate 3D elements in their representations.

5.3 Student perceptions on experiences with haptic and visuo-haptic simulations of electric fields

The third part of the research question was to "explore student perceptions on experiences with both haptic and visuo-haptic simulations". The categories in the visual + haptics phase and the sub-categories for challenges in haptics phase help answer this question.

All of the nine participants also preferred having both the visual and haptics cues for learning and understanding electric field concepts. Graph in Figure 5-6 shows general student perceptions about haptic and visual + haptic simulations. From the analysis, it was seen that all of the nine participants felt that the visual cues of force magnitude, arrows and ISO surfaces helped clarify the concepts. Six out of the nine participants felt that visual + haptics reinforces the concepts. Students felt the combined method makes the concepts concrete and cements the learning. The remaining three participants talked about the learning experience with the haptic only simulations as helpful with memory retention of the concepts learnt.

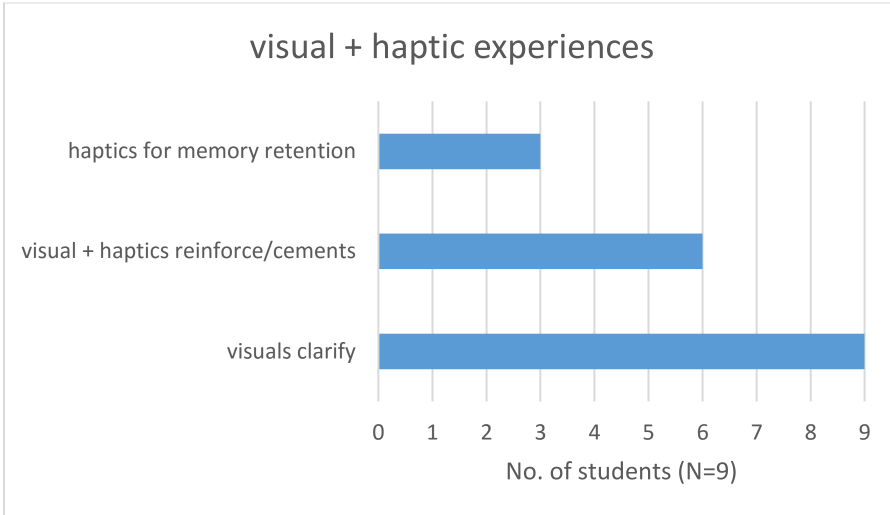


Figure 5-6. Student perceptions of visual + haptic and haptic simulations

Five out of nice participants felt visual cues help perceive the continuity of the field. Eight out of the nine participants also felt visual cues for magnitude and arrow were helpful to relate to the strength of the force felt with haptics. Five out of these eight participants also felt that the haptic feedback helped relate to the force magnitude displayed on the screen. This means that these five participants out of the nine preferred to have both haptic and visual cues to relate to the force magnitude and the corresponding strength.

All of the participants faced difficulties exploring the negative scenario for all the charge configurations. The numbers for challenges with haptic simulations are shown in the graph in Figure 5-7. The strong 'pull' and the 'vibration' experienced in the negative scenarios was distracting and made it hard for participants to understand the concepts.

Four out of the nine students also had difficulties with the device mechanics. While two of the four mistook the probe arm's stiffness to a repulsive force on the simulations, the other two suggested changes to visualizations. One of the participants thought visual cues were misleading.

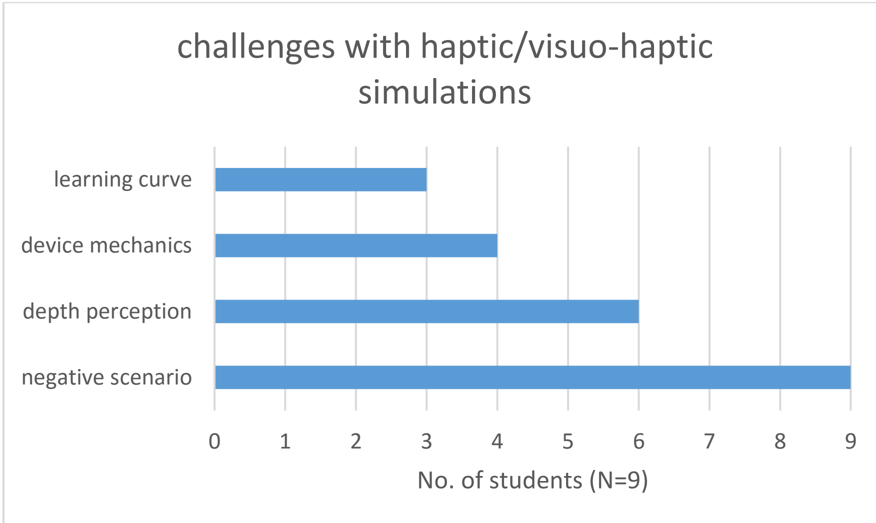


Figure 5-7. Challenges with haptic simulations

Six out of the nine students had troubles perceiving the third dimension (depth) in the haptic only simulations. Even though the remaining three students did not talk about the difficulty or show signs for the same, two of them thought aloud that visual cues helped them perceive depth better in the simulations. In general, five of the nine students said visual cues helped perceive better. Interestingly though, four of these students also thought visual cues alone were not good enough for depth perception. They thought haptic gave meaning to 3D visual cues for the simulations.

In the end, three of the nine students noted about a learning curve for haptics simulation, in the sense that it takes time to fully learn to work with the haptic simulations.

5.4 Discussion of results

The results show that students' conceptualized electric field concepts through embodied haptic experiences. As seen from the results in the earlier section, students' diagrammatic representation was heavily influenced by their sensorimotor experiences. These results support Reiner (1999)'s hypothesis that "tactile interface acts as an agent aimed to recruit the body knowledge for construction of representations similar to those in formal physics, reflecting a conceptual development of the notion of field." (p. 33).

Students also used analogies of magnets and music to draw parallels between sensorimotor experiences of abstract concepts and physical world problems. As noted by Wilson (2002) "Our mental representation of communication is grounded in our knowledge of how the transfer of physical stuff works. Thus, even highly abstract mental concepts may be rooted, albeit in an indirect way, in sensory and motoric knowledge." (p. 634). Students' use of analogies to relate to haptic and tactile experiences have been noted by other studies exploring the use of haptic learning in science education (Reiner, 1999; Jones et al, 2006).

Students' physics background or their year in the University had no influence on their predictions or representations. Three out of the nine participants had taken AP physics exams in the past (S7, S8, S9). Two of them predicted force-distance relationship correctly for the point and line charge configurations. AP physics background did not specifically seem to influence students' predictions or learning since similar predictions and observations were also made by other participants without AP physics background. Similarly, students' year in the university – whether they are freshmen (S4, S5, S7), sophomore (S1, S2, S3, S6), junior (S8) or senior (S9), had no influence on predictions or learning outcome.

Students' comments on experiencing realistic forces to relate to a visual value for force magnitude resonated with Reiner's (1999) notes on the values of sensory experiences of forces for better conceptual understanding and representation of fields. Students' perception on the relevance and importance of haptic feedback to support the visual cues for feeling the realistic forces also aligns with the findings by Schonborn, Bivall and Tibell (2011). The researchers observed that students in the haptics group, who were able to experience realistic forces with the haptic feedback, made fewer representational switches and had more realistic traversal paths for docking the ligand molecule onto the protein.

Students' challenges with device mechanics, specifically the feeling of imaginary forces, can be attributed to the inherent friction of these haptic devices. This particular challenge is also observed by researchers Escobar-Castillejos, Noguez, Neri, Magana, and Benes (2016) in their review of haptic simulators used in medical training:

> Current physical haptic devices always present a residual inner friction that can be perceived as noise, which can even fatigue the user in some cases. Additionally, the device itself has a certain degree of inertia, which present a problem if the user moves the haptic device quickly. (p. 104)

CHAPTER 6. CONCLUSION

This research study set out to seek student perceptions and experiences while learning electric fields with haptic simulations. The answers to each of the sub questions are summarized below.

6.1 Summary of results

1. How do they conceptualize haptic experiences of electric field simulations?
    a. Students used sensorimotor experiences of ‘pull’ and ‘push’ to translate the tactile feeling to electric field concepts.
    b. While most of the participants predicted the force-distance relationship and force-sign relationship in the prediction phase for point and line charge, the remaining used haptic experiences of the simulations to learn these concepts. For the ring charge however, only a couple of them were able to accurately predict the relationship in the prediction phase. The remaining participants gained the knowledge through tactile experiences in the haptics phase.
    c. Students also used analogies of magnets and music terms to relate to the type of force felt and the force-distance relationship.
    d. Students identified shape of the field, specifically 3D shapes from purely haptic feedback

   e. Some of the participants also used the embodied haptic experience as a reasoning tool to explain the null force at the center inside the ring charge.

2. How do the haptic simulations influence students' representations of electric fields and forces?
   a. Participants' representations of forces around each of the three configuration evolved from the pre-test and prediction phase to more correct and complete representation in the haptic and visual + haptics phase. None of the nine participants had a complete and correct representation of line and ring charge in the prediction phase, out of which eight and six had a correct and complete representation in the haptics phase. The remaining students had a complete and formal representation in the final visual + haptics phase.
   b. Some of the participants' representations were clearly inspired by the haptic simulations because they attempted to represent them in 3D. Six of the nine participants had 3D representation of force-feeling in haptics phase for one or more charge configurations. One of the remaining three had a 3D representation for one of the charge configurations in the visual + haptics phase.
3. What are their perceptions on experiences with both haptic and visuo-haptic simulations of electric field concepts?
   a. All of the nine participants preferred visual + haptics simulations for learning electric field concepts.

b. Participants thought that visual + haptic simulations helped reinforce and ‘cement’ concepts. Some of the participants also believed that the learning experience with haptic simulations helps with memory retention of electric field concepts.

c. While most participants felt that visual cues help understand the continuity of the field and clearly see the force magnitude, some of them also believed that haptic feedback was essential to relate to the strength of the force. The combined visual + haptics environment was preferred by most participants to work with 3D simulations.

d. Students faced challenges exploring the negative scenario because of the strong pulling nature of the force and vibration. Students also faced difficulties seeing the third dimension in haptics phase. Some of the students complained about device mechanics and a few mentioned about the learning curve to work with haptic simulations.

6.2 Limitations of the study

Following are the limitations of the study:

- The device used for the simulations is a NOVINT falcon 3D haptic controller. This is one of the cheapest devices available in the market and lacks the sophistication and capability of other more expensive devices.
- Even though the haptic probe is 3D capable, the visual images used in the haptics phase for the three charge configurations were 2-dimensional.
- The research was not conducted in a naturalistic environment. The sessions were held one-to-one between the researcher and the student. Researcher’s presence

and the probing could have affected the students' responses and experiences with the simulations.

- This being a qualitative study, subjectivity might be a concern. The results discussed here are students' perceptions and pertain only to the sample of students who participated in the study. The findings of this study cannot be generalized to a larger population.

6.3 Future work and Recommendations

Further research with haptic simulations and electric fields is necessary to conclude on the efficacy of haptics a pedagogical tool to learn these concepts. Quantitative studies designed specifically to evaluate and compare the efficacy of haptic feedback with visual in learning electromagnetism concepts must be performed. Future studies could also implement different sequences, for example, starting with visual + haptics and then working with haptics alone, to understand how that affects students' learning. Also, studies must be done with varied samples and larger sample sizes to understand the correlation and the most effective target audience for haptic simulations.

Simulations used in this haptic study implemented the attractive force in the negative scenario with a 'pull'. The directional nature of these forces could be used in the future to specifically help students differentiate between scalar and vector fields. However, students faced difficulties interpreting the pull and the associated vibration. One recommendation for future studies would be to explore other ways to implement the negative scenario. Simulations could also incorporate the 3-dimensional capability to the visual images by allowing the students to turn the source charge virtually with the probe to allow for better 3D perception.

This study focused only on point, line and ring charge configurations. It will be interesting to see how students' conceptual understanding of other configurations like sphere and plane charge configurations is influenced by haptic simulations. Sphere charge and plane charge configurations involve 3D modelling. When depicted on paper, they simply resemble a ring and a line charge. However, they are completely different configurations and haptic modelling can be used to clearly show the difference and better understand these concepts. Additionally, further studies with haptic simulations must be done with more advanced and complex electromagnetism concepts to understand how students use haptic simulations for learning more complex concepts and how they use haptic simulations for solving problems with more abstract concepts.

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APPENDICES

Appendix A: Online survey for screening participants

Dear Student,

Thank you for your interest in the visuo-haptic simulations project. The purpose of this study is to investigate the efficacy of visuo-haptic tools in understanding electric fields.

We are recruiting students to participate in the study and have an opportunity to earn a $30 value Amazon gift certificate to compensate you for your time. As an initial step, this survey is going to help us record your background and perform an initial screening process. Your responses to this survey are voluntary. All information submitted with this survey will be used for research purposes only.

Please provide your name:

Please provide your Purdue email address:

Please provide your phone number:

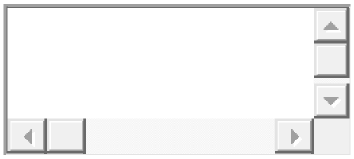
Please indicate your major:

Please indicate your academic level.

- Freshman
- Sophomore
- Junior

- ◯ Senior
- ◯ Graduate Student

Please list the physics courses you've completed so far.



How would you rate the following on a scale from 1 to 5? (1 - very poor to 5 - very good)

Academic Performance in Physics courses completed

Knowledge of Electric fields concepts

Spoken English fluency

Have you participated in a haptics study before?

- ◯ Yes
- ◯ No

Thank you for your interest in this project and for taking the time to answer these questions. We will contact you after an initial screening process.

The next step in the study consists of participating in a recorded interview, which might last up to 120 minutes. If you are selected to participate in the interview, we would like to schedule a meeting at a convenient time for you. Your responses will be confidential and your participation will not affect your grades or academic standing in any of your classes.

Please note that filling out this survey does not mean that you will be automatically selected to participate in the recorded interview. Also, only the students chosen to participate in the recorded interview will receive the $30 Amazon gift certificate, after they complete the interview.

- ☐ I agree to participate in a recorded interview.

If you have further questions or concerns, you can contact Sadhana Balachandran at balacha1@purdue.edu. You can also contact Dr. Alejandra Magana at admagana@purdue.edu.

We appreciate your participation!

Appendix B: Pre-test

Haptics study – Pre-test

Name: ____________________________________ Date: ____________________

1. What is an electric field? Give an example of another quantity that is a field. (*Source: Chabay & Sherwood, 2007*)

2. What is a point charge? Can you draw the electric field of a point charge?

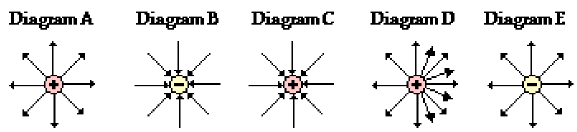
3. What is a line charge? Can you draw the electric field of a line charge?

4. What is a ring charge? Can you draw the electric field of a ring charge?

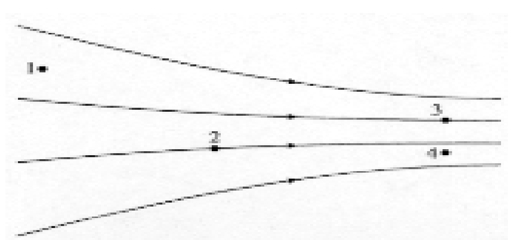
Appendix C: Progress Assessment Tests I & II

Name: ___________________________ Date: _______________

1. Several electric field line patterns are shown in the diagrams below. Which of these patterns are incorrect? Explain what is wrong with all incorrect diagrams. (*Source: http://www.physicsclassroom.com/class/estatics/lesson-4/electric-field-lines*)



2. Rank the electric field strength in order from largest to smallest. (*Source: Shaikh, U. A. S., 2015*)



   A. $E_1 < E_2 < E_3 = E_4$

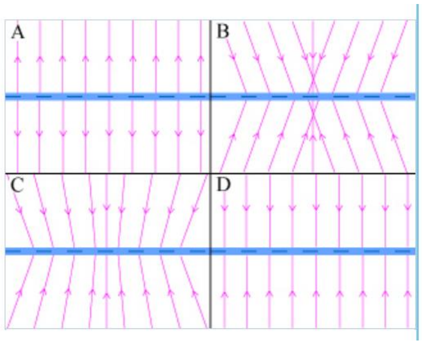
   B. $E_3 = E_4 < E_2 < E_1$

   C. $E_2 = E_3 < E_4 < E_1$

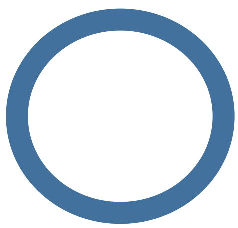
   D. $E_1 < E_4 < E_2 = E_3$

   E. Not sure

3. From the figure below, choose the panel that correctly represents the field lines from an infinite uniformly charged negative sheet and explain your reasoning. (*Source: https://www.physics.rutgers.edu/ugrad/227/HW1.pdf*)



4. Can you plot the direction of the electric field inside and outside a positively charged ring? Explain your reasoning below. (*Source: Shaikh, U. A. S., 2015*)



Appendix D: Think-aloud prompts

A. Prediction phase: Plain visuals of point charge, ring charge and line charge. No force feedback

1. What do you expect to feel? What do you predict the forces to be here?
2. What do you think will be the force at A, B and C.
3. How would the forces depend on the sign of the charge?

B. Haptics phase: Force feedback is turned on. Visuals remain the same. Questions for point charge, line charge and ring charge. Toggle between positive and negative scenarios in each case.

1. Tell me what you feel?
2. Why do you think that is happening?
3. How does that feeling translate to your knowledge of electric fields?
4. What do you think is the sign of the charge on this source charge?
5. Why do you think that is?
6. What happens when you move close to the source charge?
7. What happens when you move away?
8. What happens when you move around it at different point A, B and C?
9. Can you represent your feeling in a diagram?
10. Can you represent the electric field of this source charge?
11. How is this different from your prediction?
12. What effect did the haptic channel have on your prediction? What information do you think the force feedback is giving you?

C. Visual + haptics phase: Visualizations are turned on. Force feedback is ON. Questions for point charge, ring charge and line charge. Toggle between positive and negative scenarios for each case.

1. What do you feel now? Has the visualization of arrows changed anything?
2. With respect to visualization and the feedback from the haptic channel, please draw the electric fields.

D. General questions at the end of all simulations.

1. What do you think about the haptic feedback?
2. Which simulations do you think conveyed better meaning for you - the one with visualizations or the one without? Why?
3. What do you think about the learning experience with haptic simulations today?
4. How do you think it would affect students' learning experience if used in physics labs to learn these concepts?

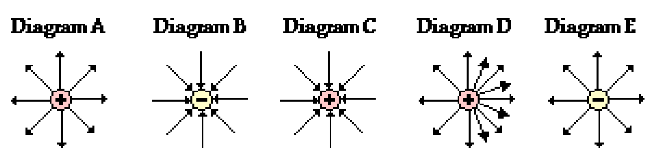
Appendix E: Pilot study Pre and post-test

Students' Reasoning with Haptic Technologies: A Qualitative Study in the E&M Domain

Student Name: ________________________________

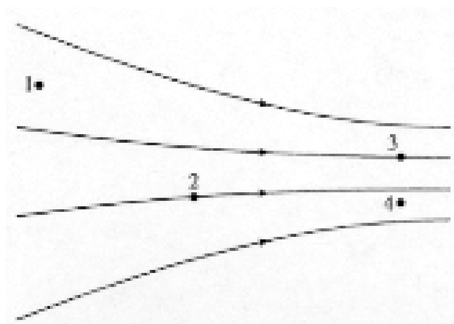
1. What is an Electric field? How do we measure electric field at a given location in space? Give an example of another quantity that is a field. (*Source: Chabay & Sherwood, 2007, p. 517-518*)

2. Several electric field line patterns are shown in the diagrams below. Which of these patterns are incorrect? Explain what is wrong with all incorrect diagrams. (*Source: http://www.physicsclassroom.com/class/estatics/lesson-4/electric-field-lines*)



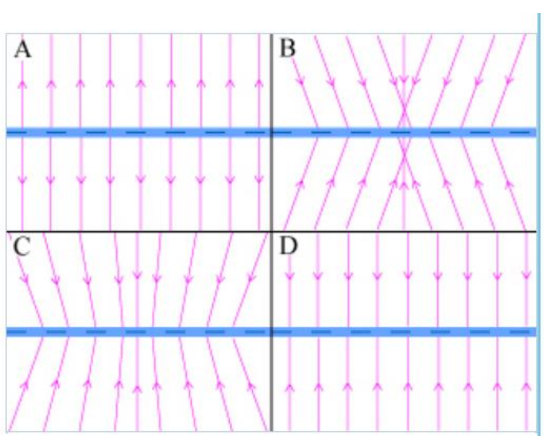
3. The charge of an alpha particle (a helium nucleus, consisting of 2 neutrons) is 2e = 2(1.6 X 10^{-19} C). An alpha particle at a particular location experiences a force of (0, -9.6 X 10^{-19}, 0) N. what is the electric field at that location? Explain your answer in as much detail as possible. (Source: Chabay & Sherwood, 2007, p.517)

4. Rank the electric field strength in order from largest to smallest. (*Source: Shaikh, U. A. S., 2015*)

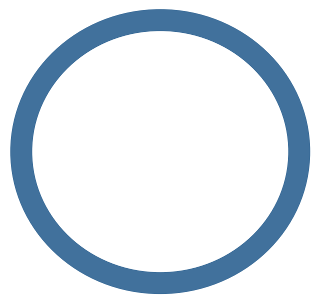


A. $E_1 < E_2 < E_3 = E_4$
B. $E_3 = E_4 < E_2 < E_1$
C. $E_2 = E_3 < E_4 < E_1$
D. $E_1 < E_4 < E_2 = E_3$
E. Not sure

5. From the figure below, choose the panel that correctly represents the field lines from an infinite uniformly charged negative sheet and explain your reasoning. (*Source: https://www.physics.rutgers.edu/ugrad/227/HW1.pdf*)



6. Can you plot the direction of the electric field inside and outside a positively charged ring? (*Source:* *Shaikh, U. A. S., 2015*)



7. Please state whether the following statement is ‘True’ or ‘False’, and explain your answer.

   “The electric field of a charged particle is unaffected by the presence of other charged particles.” (*Source: Chabay & Sherwood, 2007*)

Appendix F: Pilot study - Haptics worksheet on Electric Fields

Students' Reasoning with Haptic Technologies: A Qualitative Study in the E&M Domain

Student Name: ____

Please follow the instructions below and answer the questions.

1) Electric field for Point charge

Run the pointcharge.exe. Move the test charge (haptic) around the point charge and experience the force at different points around the point charge.

a. Write/Illustrate your observations.
b. How do you interpret the force feedback in the context of the visualization?

2) Electric Field for Line Charge

Run the lineCharge.exe. Move the test charge with the help of the haptic device on either sides of the line charge and experience the force at different points.

a. Write/illustrate your observations.
b. How do you interpret the force feedback in the context of the visualization?

3) Electric Field for Ring Charge

Run the ringCharge.exe. Move the test charge around the ring charge with the help of the haptic device and experience the force at different points around the ring charge.

a. Write/Illustrate your observations

b. How do you interpret the force feedback in the context of the visualization?

Appendix G: Pilot study - Interview questions

<u>Questions for each simulation</u>

1. Check alignment of concepts. What did you anticipate to feel when you were working with this simulation? Why?
2. What do you feel at Point A (closer to the charge)?
3. What do you feel at point B (further away from the charge)? What is the difference? Why?
4. Based on your experiences, can you draw the electric field of the source charge and the direction of the force at point A?
5. Please press the N key and observe the changes. What do you feel now?
6. What do you think happened?
7. Now for this scenario, can you draw the electric field for the source charge?
8. Imagine, that we move the source charge 5 times farther away from point A, how do you think the electric field would change?
9. If the source charge was replaced by a different particle whose charge was 7 times larger, how would this change the electric field at the observation location?

<u>Questions at the end.</u>

10. What does the haptic feedback mean to you?
11. What were your problems or challenges while interacting with the simulations?
12. With respect to point charges, line charges and ring charges, how is the learning experience with haptic devices?
13. Can you describe your experience with the haptic device today? What do you think about this approach for learning physics concepts in labs?
14. On a scale from 1 to 5, 1 being completely irrelevant, How would you rate the relevance of visuo-haptic devices in learning difficult concepts in physics?

If there is a reference to magnetic field, probe on

Why do you refer to this field as a magnetic field? When is a magnetic field produced?