# EXPLORING MULTIMEDIA PRINCIPLES FOR SUPPORTING CONCEPTUAL LEARNING OF ELECTRICITY AND MAGNETISM WITH VISUOHAPTIC SIMULATIONS

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## Abstract

This paper explores multimedia principles for a visuohaptic simulation-based approach to improve students' understanding of electricity and magnetism concepts. The study implemented different multimedia principles for incorporating visuohaptic simulations for learning guided by Multimedia Learning Theory. This study compared the use of visuohaptic simulations to a visual-only simulation and to instructional multimedia-only materials. The results indicated that students in the visuohaptic simulation group out-performed students in the visual-only simulation group and the instructional multimedia-only group; although not significantly. This paper discusses implications for teaching and learning with touch technologies.

## Introduction

There is strong research evidence that a number of abstract concepts in science exist that are not fully understood among high school and college level students [1-3]. Abstract concepts, such as electricity and magnetism (E&M), where the phenomenon is non-tangible, invisible to the naked eye, abstract, or counterintuitive, can generally result in misconceptions or alternative ideas that contradict scientific facts [2]. Even after long periods of instruction, students may not demonstrate a significant improvement in their learning performance [4]. Thus, a main concern for educational researchers and educators has been finding ways to improve current learning techniques to improve students' conceptual understanding.

Studies in the physics domain that have investigated how students make sense of E&M concepts have suggested that students often experience difficulties when learning [2, 5, 6], and overall, students' understanding of physics concepts has provided results that are below educators' expectations [7, 8]. For instance, Maloney and colleagues [2] obtained weak and disappointing results on both pretest and posttest assessments when testing more than 5000 introductory physics students from 30 different institutions utilizing their Conceptual Survey in Electricity and Magnetism. Bagno and Eylon [9] applied an electricity and magnetism written questionnaire to 250 students ages 17- 18. Their results suggest that students' understanding of these concepts can be characterized as deficient in many ways.

Specific difficulties and misconceptions have been discovered through several research studies. One difficulty relates to students' inability to use the concept of electric field in problem solving and this mistake is usually made by both high school students and even university students who have been sufficiently trained in electromagnetism [10]. Similarly, physics undergraduate students often have difficulties and experience misconceptions in understanding electromagnetic induction, electric potential and electric energy [6]. These difficulties are experienced mainly because of (a) the invisible nature of the quantities students have to operate with (i.e., electrons) [5], (b) the abstract nature of the phenomena to understand (i.e., field, flux and potential) [5], and (c) the mathematical treatment of the relationships along with the difficulty of the problem solving task [9]. Students also frequently encounter difficulties when trying to apply physics laws to electromagnetism situations. One reason for the difficulties experienced by students may be the lack of meaningful connections between concepts, such as in the case of the field concept [1]. For instance, students do not clearly observe the relationship of the concept of electric and magnetic field lines throughout mechanical and electromagnetism courses. Similarly, physics students often cannot distinguish between the concepts of fields and field lines [11], being unable to discriminate them from each other [5].

However, teaching abstract concepts in a clear and understandable format is not an easy task for instructors either. Part of the problem resides in the sequencing and the speed of the topics that are presented in a traditional introductory electricity and magnetism course. Specifically, most of the time, E&M concepts are introduced in the second half of the course, after presenting classical mechanics concepts. Even though students have performed well in the first part of the course, they frequently find E&M to be difficult and confusing [5]. Furthermore, the traditional transmission model of "gloss(ing) over it, going through the fundamentals at high speed, and spending most of the course on rote problem solving" [5], may not be effective for addressing the problem students encounter when initially exposed to the concepts [6]. This often results in student confusion and their conviction that physics consists of a large number of disconnected formulas [5]. Based on this problematic, the use of different educational strategies focusing not only on the conceptual theory, but also on the cognitive obstacles that physics university students' may encounter when learning abstract material, may be more effective than the use of traditional methods [11]. For instance, while learning the concept of field, "physics instruction should not be limited only to the formal operational definition of field strength but should include an explicit and more didactically elucidated elaboration of the field concept" [1]. Thus, the necessity for novel educational strategies that could increase the understanding and subsequent problem-solving performance of abstract electricity and magnetism concepts for physics students serve as a motivation to develop new teaching models and techniques.

The combination of different teaching methods and modalities to teach abstract concepts has been recommended as necessary for students to be able to overcome cognitive obstacles when learning abstract materials [11]. Educators believe that hands-on activities are influential learning tools that can improve student learning and performance [12]. Similarly, research suggests that students can more effectively learn abstract concepts when there is "touch" or manipulation of objects than when there is only visual support [13-15]. The use of haptic technology as a learning tool to understand these concepts has the potential to impact learning, because they can facilitate hands-on experiences. Over the last decade, researchers in the area of haptic technology have been developing low-cost haptic devices and relevant learning modules to help students connect science, technology, engineering, and math (STEM) theory with physical reality.

Using the positive results obtained from haptic technology when used as a cognitive tool for conceptual understanding of abstract science concepts as a foundation [16-20], and the necessity for novel educational strategies [11] to supplement visuohaptically-based instruction, this study aims to identify multimedia principles for a visuohaptic simulation-based approach to improve students' understanding of electricity and magnetism concepts. For the two phases of this study, we compare the immediate effect of coupling specific multimedia principles with visuohaptic simulation to other forms of instruction. The guiding research question is: *What is the efficacy of integrating multimedia principles with visuohaptic simulations to help students learn about electromagnetism concepts as compared to instructional materials and simulation only?*

The design of the simulations along with the materials was guided by Mayer's principles of multimedia for learning [21].

## Haptic Technology for Teaching and Learning

As technology evolves, new forms of simulations and visualizations are becoming available to users. These complex simulations or devices not only allow users to 'see', but also 'touch' and 'feel'; virtual objects. The technology field that focuses on the interactions of users and virtual worlds through the users' sense of touch is called *haptics*. The term "haptics" was first introduced in 1931 by Revesz [22]. The word comes from the Greek words haptikos, meaning "able to touch," and haptesthai, meaning "able to lay hold of" [12, 22-24]. Until a few decades ago, the interaction of users with computers or with visual simulations relied mostly on the users' sense of sight; although touch is one of the most fundamental ways through which people interact with physical objects [25]. Educators believe that (a) hands-on activities are influential learning tools that can improve student learning and performance and (b) haptic devices can be used as learning tools to support hands-on experiences [12]. For instance, haptic technology can simulate object hardness, weight, and inertia, and through the use of computer software, enable users to feel and explore the physical properties of virtual objects and worlds [26].

Haptic technology has recently been introduced in computer simulations for educational and training purposes [e.g., 27, 28]. Various authors suggest that the performance of psychomotor skills is better with visuohaptic feedback rather than with information transmitted through either visual or physical channels [28]. For this reason, haptic technology has been increasingly used in flight and medical training applications [e.g., 29]. Medical or flight simulations can provide students with the forces or vibrations involved in the presented scenario that resemble the feel of internal tissues and organs, or the sensation felt through a control joystick, respectively. Thus, the use of haptic force feedback supports learners' kinesthetic memory including individuals' ability to remember limb position, spatial orientation, and movement velocity [17].

Besides kinesthetic learning, haptic devices have also supported conceptual learning. Most of the exploration on conceptual learning using haptic devices has been conducted with teaching abstract concepts such as understanding the physical properties of viruses and cells [17, 27]. However, due to mixed research findings or contradictory results, the effectiveness on conceptual understanding resulting from the use of these technologies is still arguable [30]. Further research is needed to reach consensus on whether the use of the haptic devices improves conceptual learning [24, 28, 31, 32]. Recent studies have provided positive results on students' engagement and interest while working with haptic devices [17, 27]. Höst and colleagues [33] explored two interesting modes of using haptic simulation, which are referred to as the "force mode" and "force-and follow mode", where the first mode allows the learner to experience the force of the electric field and the latter allows the probe to be moved along the shape of the electric field. However, there has been little research on the use of haptic technology to teach E&M concepts. For instance, several meta analyses of literature on the use of haptic technology in educational environments have revealed a lack of research on the students' cognitive learning of E&M using haptic technology [17].

## Multimedia Principles for Learning

Multimedia Learning Theory [34] refers to the process of construction of knowledge by creating mental models from printed or spoken words in combination with pictures that could be either static or dynamic; thus, learners are found to learn more deeply from words and pictures than from words or pictures alone [34]. Multimedia learning builds upon dual coding theory by suggesting design principles that can effectively combine verbal and nonverbal information. Based on this theory, the following design principles were implemented (i) a training session for students to get used to the haptic feedback implementing the pre-training principle of multimedia learning [21]; (ii) an instructional course created in Microsoft PowerPoint introducing the concepts of E&M implementing the self-paced and modality principles of multimedia learning [35], and (iii) additional functionality and levels of interaction to the visuohaptic computer simulation utilizing the animation and interactivity principles of multimedia learning [36]. The pre-training session introduced the experience of the Falcon haptic device, so that the students would have already experienced the novelty of the technology, removing the split-attention effect of experiencing the force feedback for the first time.

Besides the content material and the different formats included in the lesson, the presentation had the functionality of being reproduced in a guided-presentation mode. This capability helped guide participants through the course's content intended order, but at their own pace. The characteristic of guided-presentation mode is supported by the self-pacing principle [37], which states that if a student has control over the rate or progress of the learning material then higher processing of information may occur.

The lesson was divided in several sections following the theory of the segmenting principle [37]. The segmenting principle states that it is better to present learners with a segmented multimedia lesson rather than with a continuous unit. The design and implementation of the different sections of the instructional lesson were also based on the signaling principle [38]. The signaling principle states that it is better for learners if cues about the purpose of the presentation are provided. Along with the instructions on the objective of the instructional course and the research study, the course presented several cues throughout its content, such as the electromagnetism topics in a menu-based slide, a Coulomb's Law formula worked-example, and indications on the end of the course and the assessment to be taken. The simulation allowed the interaction of several charged particles and the field lines were generated dynamically.

## Methods

Based on principles of Multimedia Learning [34], we investigated whether the addition of a training session, a guided activity, and the use of visuohaptic simulations influenced the performance of student conceptual understanding of electromagnetism concepts. In addition, we implemented the 'guided activity' technique [39] by embedding the use of visuohaptic simulations within an instructional learning module. This strategy allowed students to first develop an expectation of the phenomenon explored (e.g., a hypothesis to test) which was then confirmed or rejected by using the visuohaptic simulations.

The participants were divided into three groups that were exposed to different learning conditions, with a stated hypothesis that the learning condition that has access to the visuohaptic simulation will lead to a higher score as compared to the other learning conditions. Thus, the design of the study was a quasi-experimental design.

### *Materials*

The learning materials consisted of two visual/visuohaptic computer simulations and a Novint Falcon haptic device (see Figure 1 far right). The affordance provided by the haptic device consisted of kinesthetic sensing. Kinesthetic sensing is the awareness of limb positions and muscle tensions. Kinesthetic displays are usually force-feedback devices and they provide information to various body sites through force. A common type of consumer-grade kinesthetic display is the force-feedback joystick. While vibrotactile displays deliver stimulation that is abstract but very useful for notification and alert, force-feedback devices are more intuitive to the user as we naturally understand, for example, that a large resistance force implies a surface that cannot be penetrated.

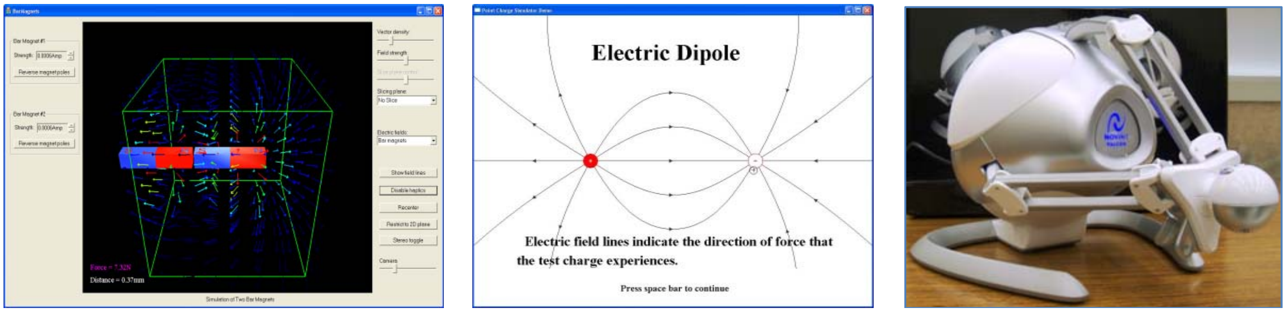
To understand the operation of a typical force-feedback device, imagine holding onto the handle of a small robot. As the user moves the handle in the three-dimensional (3D) space, the location of the handle tip is tracked by the robot and can be used as the current location of, say, a positive electrical charge, controlled by the user. Now assume that the positive charge is being moved by the user in an electrical field formed by multiple positive and/or negative electrical charges, then the force exerted on the positive charge by the electrical field can be calculated, scaled, and then sent to the handle of the robot. As the user counter-balances the robot handle with his/her hand, the user experiences the force and its variations due to the positive charge moving around in the electrical field. The haptic experience can be coupled with a real-time visualization of the positive charge being manipulated and the collection of electrical charges and the resulting electric field (field lines). This enables the user to experience the positive charge in the electrical field and how its movements interact with a static electric field.

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

The simulation used for the pre-training sesión was called Bar Magnets Simulation (BMS; left panel in Figure 1). It consisted of two 3D bar magnets with the north pole represented by the red section of the magnet and the south pole represented by the blue section of the magnet. The BMS was rendered in a 3D virtual space. Colored arrows surrounding the magnets represented field vectors. The subject domain of this simulation was magnetism and magnetic fields. The second simulation, called Charge Particle Simulation (CPS; middle panel in Figure 1), presented a 2D simulation with two static charges. A third movable positive charge, herein called test charge, could be moved around by the user using the haptic device. The static charges have their associated static electric field lines indicating the directions of their field vectors. Students were able to use the haptic device to control the position and movement of the test charge around the simulation's screen. The users interacted with both simulations using a Novint Falcon haptic device (right panel in Figure 1). Participants operated the haptic device by holding the device's ball-shaped grip and moving it in different positions at will. Force variations calculated from the current position of the grip in the magnetic or electrical fields could be felt through the grip.

In addition, an instructional PowerPoint multimedia learning course was developed (see

Figure 2). The instructional course focused on four main topics: electric charges, electric forces, electric fields, and electric and magnetic fields. Implementing the self-pace and modality principles of multimedia learning [34], the course provided basic conceptual information and presented students with videos and narrations on phenomena related to E&M. Students used arrows embedded in the course material to navigate through the content. The modified visuohaptic simulation included several new functionalities as compared to the previous version. The instructional course implemented the animation and interactivity principles of multimedia learning [34], and included additional interactivity and mobility of the charged particles. For instance, the learner was now allowed to place several particles on the screen at the same time, showing or hiding the electric field lines or force vectors interactively.



Strength: 0.0006Amp

Strength: 0.0006Amp

Slicing plane: No Slice

Electric fields: Bar magnets

Force = 7.32N

Distance = 0.37mm

Electric field lines indicate the direction of force that the test charge experiences.

Figure 1. Visuohaptic simulations (Bar Magnets and Charges Simulation) and Falcon Novint haptic device.

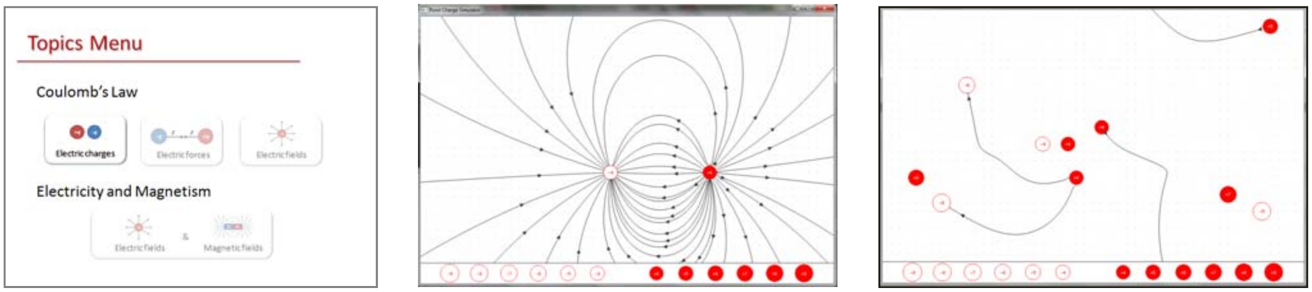


Figure 2. Main menu from the instructional course on E&M, and interactive elements of the simulation.

### *Participants*

The sample size consisted of 75 students from an Introductory Electrical Engineering Technology class (Fall 2013) offered at a Purdue University. Students from this class were evenly assigned to one of the three conditions (each group had n = 25 participants). Since the population under study were freshmen students in their first academic semester, it was assumed that their prior knowledge in E&M was similar to a 12th grader. According to high school student curricula (9 – 12 grades) from the on-line benchmarks of Project 2061, the main topic "Forces of Nature" includes concepts such as electromagnetism, motion, and magnetic forces.

### *Data Collection and Data Analysis Methods*

The data collection instrument used to collect pretest and posttest measures consisted of three questions from the CSEM [2], three questions from the questionnaire written by [4], two questions from BEMA [5], ten questions from the Diagnostic Exam for Introductory Undergraduate Electricity and Magnetism

(DEEM) from [40], and one question created by the authors (see Appendix A). The selected items covered four topics: Coulomb's force law, electric force and field superposition, magnetic force, and magnetic field caused by a current. Both the pretest and posttest electric and magnetic force assessments were administered through an online survey. Participants had only one opportunity to complete each of the assessments and questions were structured so that no question could be left unanswered.

The data analysis consisted of analyzing the collected data using descriptive and inferential statistics. During the descriptive analysis, average scores and standard deviations were calculated from the pretest and posttest scores. T-tests were used to examine possible significant differences in the results.

### *Validity and Reliability Measures*

Pre and post assessment instruments and procedures were reviewed before the implementation by three physics professors and two science educators. Cognitive interviews were conducted with a group of seven (n = 7) senior physics students who provided comments and feedback to the research design and materials. A pilot study [41] allowed the researchers to gauge the duration of the different tasks involved in the study as well as to make revisions to the learning materials, learning principles and data collection methods. We used a total of 150 student responses to the survey questions to assess reliability. Cronbach alpha [42], was used to measure the reliability of the electric and magnetic force assessment. The assessment instrument had an acceptable internal consistency with an $\alpha = 0.74$.

### *Procedures*

The study was conducted during the fifth and sixth weeks of the semester. The first week was assigned to the training of the students on the use of the haptic device. All participants were exposed to the Falcon device at the beginning of their laboratory session and were able to explore the visuohaptic simulation BMS for a period of 20 minutes. The following week the study took place throughout the whole period of the laboratory session (1.5 hours). The procedures began by having students complete the online pretest assessment while in the lab. Students were instructed not to consult any external materials and to complete the test individually. Then, when all students had completed the test, participants opened and completed the instructional course.

As described above, each treatment had some similarities and differences. Similarities included exposure to a self-paced instructional multimedia course. Differences included exposure to a visual simulation (using a computer mouse), exposure to a visuohaptic simulation (using the Falcon) and no further exposure to additional learning materials). Participants from the three treatment groups were then allowed to respond to the online posttest assessment.

## Results

Participants' responses were coded as incorrect (0) or correct (1) and were analyzed statistically within and across learning conditions. We also compared pretest scores from all the three conditions to identify if students started at the same level, and we concluded that students from the three groups started at a similar knowledge range (F=0.202, p=.818). Table 1 shows a summary of the descriptive and inferential statistics for the pretest and posttest measures for each of the three conditions.

Results from the pretest measures suggest that overall, students from all conditions performed poorly in demonstrating their conceptual understanding of E&M related concepts by scoring approximately 8 questions correct out of 19. The descriptive statistics from the posttest measures, showed that students improved their performance to an acceptable level (~60%), suggesting that the three conditions had a positive impact on students' learning performance. The analyses within condition consisted of comparing pretest assessments to posttest results using a two sample t-test. Table 1 also shows that there was a positive increase for all three conditions and the three conditions were significantly different from zero (p<.05). The ANOVA analysis found no significant differences (p=0.075) among the three groups for the post test.

Table 1. Descriptive and inferential statistics for the three different group conditions.

| | | Pretest | | Posttest | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Condition | N | Mean | Std. Dev. | Mean | Std. Dev. | t | p-value | Mean Gain | F | p-value |
| Group 1: multimedia instructional course | | | | | | | | | | |
| | 25 | 7.88 | 3.08 | 10.84 | 3.77 | -5.751 | .000 | 2.96 | 2.691 | .075 |
| Group 2: Multimedia instructional course + visual simulation | | | | | | | | | | |
| | 25 | 8.44 | 3.44 | 10.44 | 3.83 | -2.730 | .006 | 2.00 | | |
| Group 3: Multimedia instructional course + visuohaptic simulation | | | | | | | | | | |
| | 25 | 7.92 | 3.86 | 12.00 | 3.15 | -6.400 | .000 | 4.08 | | |

## Discussion

The learning design of this study implemented different strategies that aimed to reduce possible cognitive overload [43]. Previous studies that have investigated the effect of the use of haptic technology for conceptual understanding in electricity and magnetism have reported mixed results. For example [41] resulted in positive effects on both conditions (i.e., visual-only and visuohaptic), where students improved their performance from pre to posttest assessments. However the visuohaptic condition did not perform better than the simulation only condition. Potential explanations for this result can be the combination of complexity of the abstractions of the phenomenon under study and the novelty of the force feedback. We believe that the novelty of the force feedback may have overloaded learners' working memory capacity [43], and therefore no significant gains were identified as compared to the control group.

Cognitive overload occurs when the information processed exceeds the cognitive capacity of the learner [43]. The procedure of unifying the information requires working memory space from the learner to process the different information formats, leaving less working memory capacity for learning processes for schema acquisition [21]. Students working with the haptic device and with the visual simulations might have been exposed cognitive overload due to the different formats through which information was presented.

Our study implemented scaffolding methods within the learning design, which were guided by the following principles of multimedia learning [34]: (a) the pretraining principle, with the goal of removing a distracting effect of the novelty of the haptic device; (b) the self-pace, modality, and segmenting principles providing students with additional learning materials with navigation controlled by students; and (c) the animation and interactivity principles providing additional functionality and testable scenarios with the simulation tool.

Results from our study suggest that these modifications significantly improved the learning experience. Students from the three groups increased their performance from a low to a moderate level, suggesting that multimedia learning principles implemented may have reduced cognitive load. Furthermore, students in the visuohaptic simulation group outperformed students from the other two groups, although not significantly.

## Implications for Teaching and Learning

Cognitive Load Theory (CLT) describes how cognitive load of working memory capacity results from three different sources [44]. These three sources are (a) intrinsic cognitive load caused by the complexity of the information or task being processed (b) extraneous cognitive load due to the presentation of information based on its design, and (c) germane cognitive load that relates to the effortful learning process. These three additive sources work as follows “given a certain intrinsic cognitive load, an increase in extraneous cognitive load implies a decrease in the working memory capacity available for germane cognitive load” [45] .

Principles of Multimedia Learning implemented as part of the revisions may have contributed to a reduction in cognitive overload. For instance, Mayer and Moreno [21] suggested that when two information channels (i.e., visual and auditory) are overloaded with essential processing demands, pretraining is an alternative technique for reducing cognitive load. Pretraining consists on providing learners with prior instruction regarding to some of the components of the to-be-learned system. In our study, the learners received pretraining concerning (a) the use of the haptic device a week before implementing the learning experience and (b) an introduction to E&M principles by means of an instructional module. Another strategy that might have contributed to reducing student cognitive load, may be attributed to the use of segmenting [21]. In segmenting, the presentation of the materials was broken down into smaller portions by first presenting the multimedia learning module and then the use of the simulation tool (or visuohaptic simulation tool). Presenting the material in this way, the learner might have had an opportunity to organize and integrate the material to be learned.

Schönborn et al.'s [46] hypothesized the extraneous load can be reduced by combining visual and auditory information, the combination of haptic and visual modalities may also potentially expand working memory capacity that can be devoted to germane processing. Their study found that students in a visual-only group were subjected to high visual representational holding demands demonstrated by high representational switching activity between different visual representations of chemical structure. However, subjects in a visuohaptic condition displayed half the amount of these switching behaviors, and the presence of the haptic feedback allowed this high processing demand to be "offloaded" onto the haptic processing channel. The hypothesis of dual visual and haptic processing could be derived from Moreno and Mayer's [39] cognitive-affective model of learning that postulates five separate sensory channels, where the "tactile" and "visual" sensory memories would be the two "channels" at play in the former interpretation.

In summary, the results from our study show some promise on the integration of haptic technology for conceptual learning. The students in group three who were exposed to the visuohaptic simulation outperformed the other two groups in the posttest measures, although the results obtained from the ANOVA analysis suggested no significant differences among the three groups. As pointed out by Jones and colleagues [16] who also investigated the efficacy of force feedback, the sample size could have affected the possibility of finding significant differences.

### *Implications for Teaching*

Our results have implications for teaching abstract concepts such as E&M. Instructions should focus on the level of difficulty that the concepts provide to learners. For example, according to [5] courses often do not present a connection between electricity concepts, which later increases the confusion students experienced as they do not link topics and information. According to research, some methods and techniques that can ease this difficulty include the use of simulations. Research has proven that the use of simulations improve or even assimilate students' learning as compared to students who use real physical equipment [47]. The correct selection of learning materials and physics topics should be a priority for instructors. However, if these learning materials could provide an extra value to student's learning, such as the use of simulations, then instructors should consider their use. On the other hand, instructors should also be aware of different pedagogical approaches and design principles that can help them to effectively use computer simulations for learning; where a combination of direct instruction and discovery learning approaches may be some of the most effective ways [48].

In the present study direct instruction was supplemented with the instructional multimedia learning materials but discovery learning approaches were not directly integrated. Combining both approaches may enable students to benefit more from the learning process in general, and from the haptic feedback specifically. However, further investigation is needed to identify the effect of this combined approach.

The Novint Falcon is a low-cost haptic device targeting the gaming industry, with a peak force around 10 N. Although it can be expected that the Falcon will have less optimal device characteristics compared to the more expensive Phantom, its current pricing is by far better keeping a classroom or laboratory setup in mind.

### *Implications for Learning*

Recent developments and research on teaching methods include the use of simulations coupled with haptic devices. The addition of haptic information to visual and audio formats is thought to be beneficial to learners based on the theory of embodied cognition [49, 50]. The force feedback provided by haptic devices allows students to "feel" phenomena that cannot be observed or experienced directly. According to the embodied cognition theory, students learn not only through their conceptual system but also through their perceptual and psychomotor systems [51]. However, in order to take full advantage of the use of haptic technology, we must first identify the forms of interactions that can exploit the haptic technology. That is, we need to find new uses or new movements or manipulations to interact with and that go beyond the uses of a computer mouse. Similarly, we need to identify new learning strategies that can support learners in encoding or translating haptically-gained knowledge into conceptual understanding.

The potential promise and outcomes of visuohaptic environments suggest that they may be related to multiple factors including the requirements of the task to be performed, the learning context, semantics of the science concepts to be learned, and the interactive affordances of the technology. For instance, Schönborn et al. [52] report findings that allude to the fact that precise co-location of the 3D visual object and haptic volume assisted in a favorable cross-modality for performing the task, which suggests that in this case the bimodal integration was beneficial for conceptual understanding. Moreover, Viciana-Abad & Reyes-Lecuona [53] have suggested that visual cues lose importance if they are not co-located. Similarly, Palmerius & Forsell [54] have demonstrated significant differences between different haptic feedback designs in the processing of haptic virtual workspaces. In this vein, other educational research has not always revealed a significant conceptual benefit of bimodal visual-haptic processing [55]. It appears that the nuances of different visuohaptic set-ups and corresponding tasks have a remarkable influence on the measured outcomes.

Implications for learning in similar instructional scenarios should focus on whether students are cognitively prepared for new educational technology equipment. Even though students have a higher level of exposure to new technology and devices nowadays, exposure to experiencing different learning effects such as cognitive overload and split-attention effect are still prevalent. Instructors should be aware that providing a different and innovative learning technique to students could contribute to cognitive overload. Adequate training or guidance on the use of the novel equipment could prepare students' cognitive learning and enable them to acquire a higher level of conceptual understanding and prevent the negative learning issues. This training or guidance can result in students' ability to perceive force variations more readily and be able to translate them conceptually.

## Conclusion and Future Work

Results from this study suggest that the additional force feedback provided by the haptic device contributes to a better understanding of concepts related to E&M. We found that students from the three treatment groups improved their understanding of the concepts of E&M as shown by the significant increase in test scores from pretest to posttest. We attributed these changes to the positive effect of multimedia learning principles that were aimed to reduce possible cognitive overload. However, the educational potential of the haptic technology for conceptual understanding by touch still needs further investigation.

Science and engineering educators along with educational researchers have argued that design of guidance to ensure that students benefit from the use of computer simulations remains the most crucial variable in the success of science and engineering instruction [56]. This study has taken steps towards identifying what are possible design principles that can guide the use of visuohaptic simulations. However, to design powerful guidance, iterative trials in instructional settings and corresponding refinement processes are necessary [56].

There are several possible avenues for future work that include the implementation of guided-inquiry approaches to be able to make stronger conclusions of the benefit of the implemented principles. Designing both the instructional and assessment materials that focus more on the haptic modality will also be an important aspect of our future work. For instance, we need to identify new learning strategies that integrate different forms of interactions such as utilizing touch analogies for different scientific concepts, or if the force feedback need to be calibrated differently (i.e., quadratic, linear, and constant feedback) depending on the scenario, so students are more sensitive to the changes [57].

However, these relationships were not found for projects 2 and 4. Moreover, projects 2 and 4 showed the highest scores among all the projects with the lowest standard deviation. The main difference between these two groups of projects is that, in projects 2 and 4 students were provided with more information about how to structure the underlying algorithm. This additional structure was necessary since the subject of the modules, ordinary and partial differential equations were not subjects with which students were familiar prior to the course. The additional support provided in crafting the algorithm appears to have been sufficient for students to properly implement a solution. On the other hand, because of the higher level of scaffolding, students may have been less engaged in higher order levels of thinking, limiting their ability to interpret their solution. Another possible explanation relates to the nature of the scaffolding that was provided. The scaffolding was focused on the algorithm structure, but the disciplinary and mathematical content may have become the challenge to interpret the results of the simulation.

Finally, the fact that student score for project 4 was weakly related to the course score also suggests that the additional scaffolding provided for project 4 may not have necessarily contributed to the overall learning outcomes. Nevertheless, project 4 needs to be further explored in order to understand its particularities.

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# Appendix A

Pretest and posttest assessment questions.

| Authors | Questions(Answer) |
|---|---|
| [2] | 1. The original magnitude of the force on the +Q charge was F; what is the magnitude of the force on the +Q now? (3)<br>2. What is the magnitude of the force on the +4Q charge? (4)<br>3. Now what is the magnitude of the force on the +4Q? (5) |
| [4] | 4. A small wooden ball [at rest] with charge Q positive (5.a)<br>5. A small copper ball [at rest] with charge Q positive (5.b)<br>6. A small iron ball [at rest] without net electrical charge (5.c) |
| Research authors | 7. A small iron ball in movement with charge Q negative |
| **[21]** | 8. What is the direction (a-j) of the electric field at location 1 (marked with an ×)? (4)<br>9. What is the direction (a-j) of the electric field at location 2 (marked with an ×)? (5) |
| **[40]** | 10. For the figure in the box, the net electric field at the cross points. (10)<br>11. If you chose answer "e" in question 10, then skip this question and go directly to question 12. Relative to the magnitude of electric field at the cross in the figure for question 10, what would happen to the magnitude of the electric field at the cross if the cross were farther to the right? (11)<br>12. For the figure in the box, the net electric field at the cross points. (13)<br>13. If you chose answer "e" in question 12, then skip this question and go directly to question 14. Relative to the magnitude of electric field at the cross in the figure for question 12, what would happen to the magnitude of the electric field at the cross if the cross were farther to the right? (14)<br>14. For the figure in the box, the net electric field at the cross points.(40)<br>15. For the figure in the box, the net electric field at the cross points.(41)<br>16. What is the relationship, if any, between the net electric field at the cross in question 14 and the cross in question 15? (42)<br>17. For the figure in the box, the net electric field at the cross points.(43)<br>18. For the figure in the box, the net electric field at the cross points (44)<br>19. What is the relationship, if any, between the net electric field at the cross in question 17 and the cross in question 18? (45) |