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RESEARCH ARTICLE

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Undergraduate students' conceptual interpretation and perceptions of haptic-enabled learning experiences

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Abstract

Although visualization remains a primary mode of interaction in simulations, touch is the most common way people use to interact with the physical objects. A greater sense of immersion in a learning environment can be reached when the user is able to feel and manipulate objects as compared to only seeing or listening. Despite the affordances of haptic technologies, which could serve as scaffolds for deep conceptual learning, their true potential in education has not been fully harnessed and little research has been done to investigate its effectiveness for learning difficult concepts. This study explores the potential of haptic technologies in supporting conceptual understanding of difficult concepts in science, specifically concepts related to electricity and magnetism. A pretest-posttest study identified if students improved their conceptual understanding of electricity and magnetism concepts. Specifically, this study identified (a) how students, with different physics background, conceptually interpreted the tactile learning experience in the context of the visualization, and (b) students' perceptions on the use of haptic technologies for their learning, as well as their perceived usefulness and ease of use. Our results suggest that overall students significantly improved their conceptual understanding about electric fields for distributed charges after being exposed to a visuohaptic simulation guided activity. Regarding students' prior coursework, students with high school-only physics background outperformed students who have been previously exposed to college-level physics courses 8% higher in the posttest average score. Similarly, students overall agreed that they enjoyed using the haptic device for learning and found the technology as easy to interact with. Implications for teaching and learning are provided as well as venues for future work.

Keywords: Electricity and magnetism, Science education, Multimedia learning, Visuohaptic simulations

Introduction

Touch is a powerful sense that humans are born with. Touch is referred to the sense through which information is received by receptor systems in the skin and body (McLinden & McCall, 2016). Active touch, as opposed to passive touch, involves the active exploration and manipulation by stimulating receptors systems in the muscles, tendons and joints; that is, in the kinesthetic system. The sense of touch can afford unique interactions with and obtain information from the real world such as (a) acquiring information about external objects through static touch, (e.g., temperature); (b) exploring objects using hand movements to discover texture, hardness, folds and outline; and (c) investigating different types of objects by manipulating them, such as identifying objects' shape and weight (McLinden & McCall, 2016). Although touch is one of the most fundamental ways through which people interact with the physical world (Thurfjell, McLaughlin, Mattsson, & Lammertse, 2002), surprisingly little is used as a vehicle for conceptual learning, particularly in higher education.

Haptic devices are special electro-mechanic apparatus controlled by a computer, usually via a USB port. Haptic devices (see Fig. 2d) include a handle that can move in 3D space and is connected to a base by a mechanical hand that is controlled by several (usually three) step engines. The user grabs the handle and moves it in 3D space. The handle tracks the position that is sent to the computer and the computer sends signals to the step engines. They, in effect, generate a force that is perceived as a force feedback by the user. An example of a simple haptic simulation is a viscous drag that is that can be perceived as the effort when moving a spoon in a jar of honey. As the user moves the virtual spoon, the computer generates corresponding force feedback that slows the movement down. The key issue in haptic devices is the development of the corresponding simulations. Nowadays, haptic technologies are becoming more affordable and accessible to various applications, including education. Haptic technologies have the potential to become a revolution in the way we interact with computers and the virtual world. However, more research is therefore needed to effectively integrate haptics technology for educational research. To adopt these technologies in educational settings, it would be important to provide concrete evidence that the use of haptics technology in learning creates a cognitive impact.

Haptic technologies can enable the sense of touch in a virtual world, allowing users to perceive different sensations like hardness, shape, weight and texture of virtual objects in computer visuohaptic simulators (McLaughlin, Hespanha, & Sukhatme, 2002). Although visualization remains a primary mode of interaction in simulations, touch is the most common way people use to interact with the physical objects (Thurfjell et al., 2002). Therefore, a greater sense of immersion in a learning environment can be reached when the user is able to feel and manipulate objects as compared to only seeing or listening (Srinivasan, Beauregard, & Brock, 1996). Despite the affordances of haptic technologies, which could serve as scaffolds for deep conceptual learning (Jones & Magana, 2015), their true potential in education has not been fully harnessed and little research has been done to investigate its effectiveness for learning difficult concepts (Minogue & Jones, 2009). Furthermore, the sparse research in this area has not seen conclusive results (Zacharia, 2015).

Topics in electricity and magnetism, such as the electric fields produced by distributed charges, are concepts that have received little attention in regards to the implementation of haptic technologies. Sanchez et al. (2013) investigated the efficacy of using visual only and visuohaptic simulations for improving the learners' understanding of electromagnetic concepts. The findings of this research, however, were inconclusive. In a similar work, Neri et al. (2015) used a visuohaptic simulation in order to illustrate the dependency on distance of the electric force strength exerted on a test point charge by different charge distributions, for a sample of undergraduate engineering students.

Although the learning gain obtained by students of an experimental group was on the average larger than that obtained by students of a control group, these results were inconclusive due to the rather small student sample.

This paper shows a study that further explores the potential of haptic technologies in supporting conceptual understanding of difficult concepts in science, specifically concepts related to electricity and magnetism. The research questions for this study are:

1. Can technology undergraduate students (with varying physics backgrounds) improve their conceptual understanding about electric fields for distributed charges after a guided exploration with visuohaptic simulations?
2. How are students making meaning of the force feedback in the context of the visualization?
3. What are students' learning perceptions after using the visuohaptic simulations to learn the concepts of electric fields for distributed charges?
4. What are students' perceived usefulness and ease of use of haptic technology for learning?

Understanding electricity and magnetism

Educational researchers have suggested that it is crucial for students to have a strong understanding of electricity and magnetism concepts (E&M) because they are the foundation to advanced concepts in physics (Chabay & Sherwood, 2006). E&M is also the basis to the understanding of behaviors of many current and novel technologies such as abrasive paper, powder coating, computer hard drives, and magnetic resonance imaging scanners, among others. From the perspective of an instructor, finding effective teaching mechanisms of such unobservable and abstract phenomena in an effective and comprehensible format is a well-needed effort. The traditional classroom approaches for teaching E&M concepts alone, however, are not beneficial for a strong fundamental understanding (Dega, Kriek, & Mogese, 2013). Students often are overwhelmed with coursework, making it difficult to take the time to garner a deep understanding of these fundamental concepts. Specifically, focusing more on solving the mathematical problems using equations rather than spending time on helping students develop appropriate explanations of the core fundamental concepts may be a more appropriate approach (Chabay & Sherwood, 2006).

Several learning difficulties of E&M have been identified at the high school level. Specifically, it was identified that students are deficient in (1) grasping central ideas associated with the E&M concepts, (2) attaining conceptual understanding and (3) gauging the relationship between concepts to solve problems (Bagno & Eylon, 1997). Similarly, another study with more than 5000 undergraduate students identified difficulties such as (a) students' struggles to apply Newton's third law or symmetry of Coulomb's law to electric point charge situations, (b) students' inability to identify how a new charge affects the direction of the force or field, or (c) students' confusion in identifying magnetic field effects from electric field effects, among others (Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2001).

Difficult and abstract concepts in science can be represented using effective computer simulations (Dega et al., 2013). For instance, Jimoyiannis and Komis (2001) compared the fundamental understanding gained by two groups of students about the physics concepts of acceleration and velocity. Both the control and experimental groups attended a lecture, whereas the experimental group additionally worked on computer simulations. The experimental group showed significantly higher gains. Computer simulations however, when enhanced with haptic technology, can further enhance students' understanding of difficult, abstract and unobservable phenomena in science (Minogue & Jones, 2006). By integrating haptic technology with computers, instructors can create virtual laboratories where students can have a hands-on learning experience (Escobar-Castillejos, Noguez, Neri, Magana, & Benes, 2016). Current applications of haptic technology can be seen in the field of geoscience, medical science, 3D modeling, entertainment and mechanical simulations (Pantelios, Tsiknas, Christodoulou, & Papatheodorou, 2004). Educators believe that hands-on activities are influential learning tools that can improve student learning and performance (Minogue & Jones, 2006). Haptic devices as learning tools can facilitate hands-on experiences. Research studies have reported positive results regarding the effectiveness of conveying abstract concepts when there is "touch" or manipulation of objects as compared to instruction where there is only visual support (Jones & Vesilind, 1996). However, previous research exploring conceptual understanding has not reported any consistent results to provide firsthand evidence for the existence of the cognitive impact of haptic technology (Neri et al., 2015; Sanchez et al., 2013).

Cognitive-affective theory of learning with media

The theoretical framework which guided the current study is based on the cognitive-affective theory of learning with media (CATLM) (Moreno & Mayer, 2007). The basic idea proposed by the CATLM framework is that effective learning occurs when there is a clear integration of prior knowledge with new knowledge leading to coherently structured form of knowledge. Moreno and Mayer's (2007) cognitive-affective theory of learning with media points out four crucial principles of learning with multimodal learning environments. As shown in Fig. 1, there is a separate processing modality for different instructional media.

The working memory has limited processing capacity for each modality. For learning to be effective, any new information needs to be appropriately selected, organized and integrated with existing knowledge. Motivation is a crucial factor when the learner

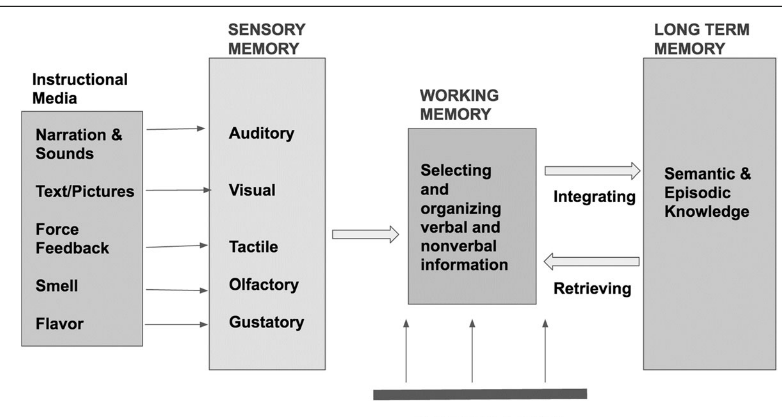

Fig. 1 Elements of the cognitive-affective theory of learning with media (Moreno & Mayer, 2007)

engages in a multimodal environment. They also suggested that at a given time only a limited number of elements could be processed by the working memory. Learners can possibly learn more effectively when they are not required to process excessive information corresponding to one modality only. Wong et al. (2009) suggested that when there is more strain on one of the processing modalities while interacting with a multimedia environment, it could lead to a potential cognitive overload. For instance, when a learner is exposed to a lot of visual information, it can overload the visual working memory of the learner (Mayer & Moreno, 2002). Such a cognitive overload may limit the resources available to make connections between information from different channels (Austin, 2009). Learning can be more effective and have a deep-seated influence, if learners are not overloaded with excessive information from a specific sensory channel.

Learning materials

The implications of the theoretical framework for the design of the learning materials relate to the integration of the five design principles proposed by CATLM (adapted to our study in Table 1). The five principles were fulfilled as described next. First, a guided laboratory report was the main vehicle to scaffold the learning experience implementing principles such as guided activity, reflection, and feedback from the CATLM framework (Moreno & Mayer, 2007). The guided activity principle was implemented by allowing students to explore the forces felt by a point charge (test charge), controlled by the cursor, at three different points of a certain electric charge configuration, followed by a comparison among these locations. The sign of the test charge can be switched from positive to negative. Three visuohaptic simulators were designed for this

Table 1 Adaptation of CATLM principles for the learning design

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

purpose: another (fixed) point charge, an infinite (straight) line charge and a ring charge. These charge distributions have positive sign, and the charges of the line and of the ring are uniformly distributed. Hereafter, the infinite line charge will be simply referred to as "line charge". Specifically, the learner can change the distance between the test charge and a particular charge distribution by moving the cursor (input variable) and can feel how the strength and the direction of the electric force are modified (output variables). Secondly, the reflection principle was implemented in order to guide students through their thinking process. Accordingly, students were prompted to describe the force they felt in every instance of the guided activity. Once students described the force felt, they were prompted to also interpret the sensation in the context of the visualization. Therefore, students were able to test their understanding of the nature of the electric forces produced by each charge configuration by means of the force feedback provided by the haptic device. To this end, the explanatory feedback principle was therefore replaced with perceptual feedback provided by the haptic device. On the other hand, students were allowed to perform the activities of the laboratory report at their own pace allowing them to process the information for each configuration one at a time. Finally, before engaging with the laboratory experience, students were able to get familiar with the haptic manipulation and feedback through a pre-training session.

The laboratory experience consisted of the three simulations corresponding to the point, line and ring charges (Figs. 2a, b and c, respectively), a lab report to facilitate a guided learning experience and a haptic device. Novint Falcon haptic devices were used to provide force feedback with three degrees of freedom, and the Chai3D framework was chosen for graphic and haptic rendering. The Novint Falcon (Novint Technologies, Inc.) is an affordable haptic device that has been primarily developed for 3D games and it can handle a peak force of around 10 N.

To understand the operation of the force-feedback device in the context of our simulation, 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 a test electric charge, controlled by the user. That is, the user can control the position of the charge (i.e., the test charge) where the charge point is used to navigate the scene. Now assume that the test charge is being moved by the user in the electrical field formed by a given electric charge distribution in the vicinity, and then the force exerted on the positive test 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 the hand, the user experiences the variations of the force on the test charge moving around in the electrical field produced by the charge distribution. The haptic experience is coupled with a real-time visual animation of the test charge being manipulated, the electric charge distribution and its resulting electric field (field lines). This enables the user to experience the strength and direction of the force exerted on the test charge by the electric field and how these change according to its motion around a static electric field.

Methods

A pretest-posttest study aimed to identify if students can improve their conceptual understanding of E&M concepts was implemented. This study specifically identifies

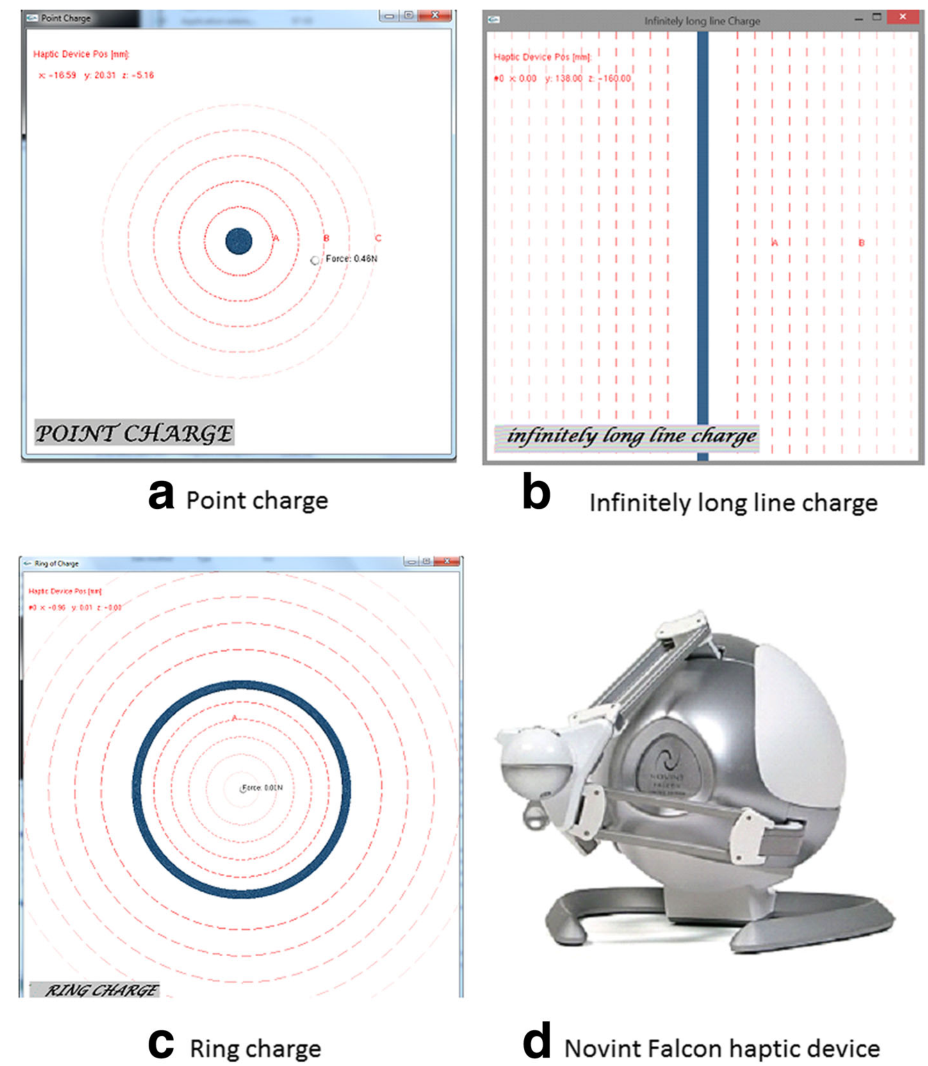

Fig. 2 Screenshots of our visuohaptic simulations (**a**–**c**) and the haptic device (**d**)

how students, with different physics background, conceptually interpret the tactile learning experience in the context of the visualization. The study also explores students' perceptions on the use of haptic technologies for their learning, as well as their perceived usefulness and ease of use.

Participants

The participants for this study consisted of 30 undergraduate technology students from a Mid-Western University in the USA. The learning intervention was not part of the curriculum. Therefore, the study was conducted outside of the classroom. Students were recruited via flyers, announcements in three different classes at the freshmen or sophomore level, and through a booth at the lobby of the building where students had an opportunity to try the haptic device. Students who signed up to participate were selected on a first-come first-served basis. The researchers contacted each student separately and scheduled a one-hour individual session outside of class and whenever their scheduled permitted. Twenty-two students, from non-physics majors, took at least one undergraduate Physics course covering topics such as electricity, light, and modern physics. The remaining eight students did not take physics courses at undergraduate level. All the students had exposure to physics courses at high school level.

Data collection method and procedures

Selected questions from textbooks and journal publications were used to evaluate the participant's conceptual knowledge of electric field for distributed charges. The pretest and posttest instruments were identical, and included questions from each of the three charge configurations (namely point, line and ring charge), consisting of nine items. The study started by first asking students to fill out an introductory survey, which was designed to collect information about the student's major, academic level and their physics background. Afterwards, students were exposed to a 20-min pre-training session (Mayer, Mathias, & Wetzell, 2002). Students explored some sample Chai3D simulations to get familiarized with the haptic device. Next, the students worked on a short guided learning experience with a visuohaptic simulator involving the concept of buoyancy. The students could change the object size and density, the liquid density and feel the changes in the buoyant force. This activity was intended for students to get used to the haptic feedback.

Conceptual learning assessment

Student conceptual learning was measured with a pretest assessment. After practicing with the visuohaptic simulators, learners were then evaluated for a gain in conceptual understanding using a posttest, which was identical to the pretest. Pretest and posttest assessment questions and their sources are shown in Figs. 3, 4, 5, 6 and 7.

Once students responded to the pretest assessment they were asked to launch the visuohaptic simulations for the three charge configurations (i.e., point, line, and ring charge). Students were guided through the learning experience via a laboratory report. The format of the laboratory report was designed with the intention to provide the students with a guided learning experience (Moreno & Mayer, 2007). The students worked

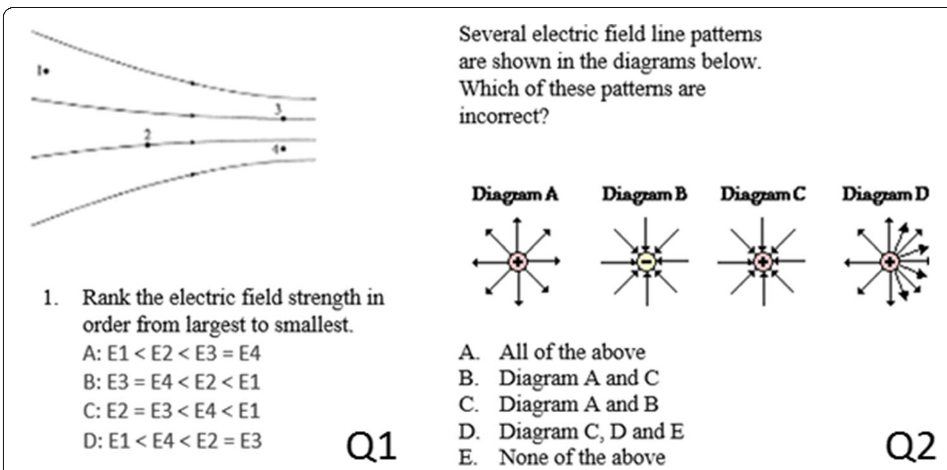

Fig. 3 Questions for general understanding. *Q1* Source: http://dev.physicslab.org/Document.aspx?doctype=3&filename=Electrostatics_ContinuousChargedRod.xml. *Q2* Source: http://faculty.spokanefalls.edu/InetShare/AutoWebs/miker/Physics%20202/Chapt%2027,2/27_WorkBookSolutions.pdf

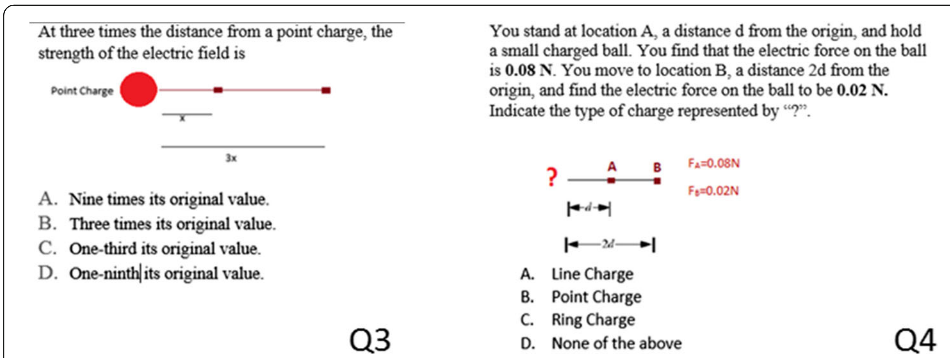

Fig. 4 Questions for point charge configuration. *Q3* Source: Question developed by the researchers. *Q4* Source: http://www4.ncsu.edu/~beichner/PY208/Docs/resources/Clicker%20Questions/Clicker%20Questions.html

on the laboratory report while they explored the three different electric field simulations one by one.

Force feedback interpretation questionnaire

As students worked through their laboratory report, they were prompted to respond to several force feedback interpretation questions. For each of the three configurations (i.e., point charge, line charge and ring charge), students were asked to explore them and at the same time record their observations by describing the force felt at three different interesting points within the visualization. The points were selected purposefully so we could guide students in their thinking by testing the forces felt at each of the designated locations. Students first tested the forces felt at each location independently, and they were then prompted to compare them. For each point (i.e., locations A, B, and C), and for each charge configuration, students were asked to report their thinking by answering the following questions: What are your initial observations? What do you feel? How do you interpret the force in point X in the context of the visualization? To elicit students' comparisons of the forces felt at the three points, students were then asked: What is the difference or relationship between the forces felt at points A, B and C (do they increase or decrease, and at what rate?) Finally, students were prompted to explore the effect of changing the sign of the test charge and report their observations about variations in the force exerted on it by the different charge distributions: Press

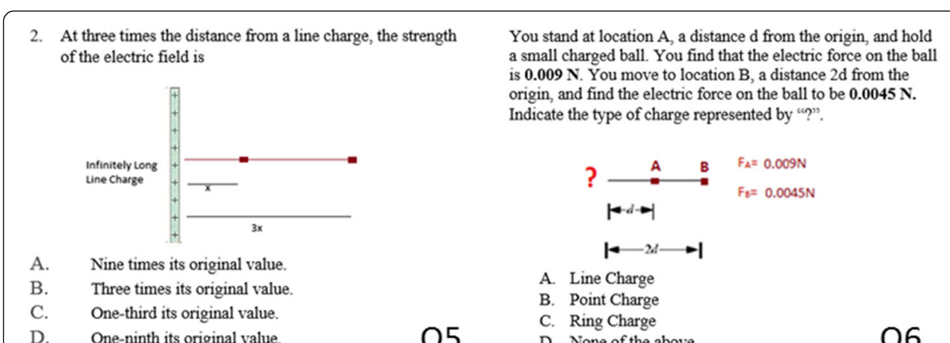

Fig. 5 Questions for infinitely long charge configuration. *Q5* Source: Question developed by the researchers. *Q6* Source: http://www4.ncsu.edu/~beichner/PY208/Docs/resources/Clicker%20Questions.html

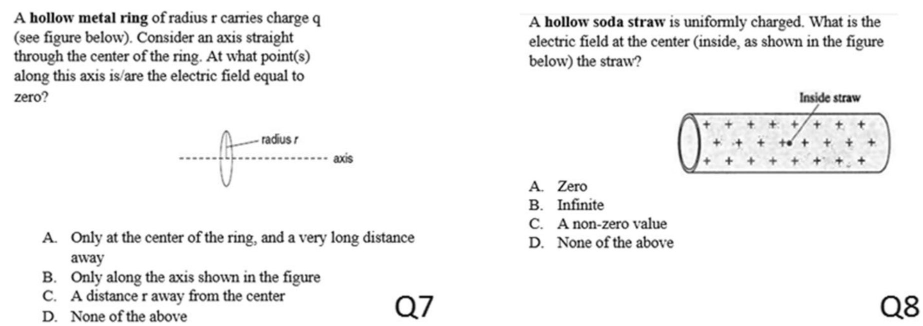

Fig. 6 Questions for ring charge configuration. *Q7* Source: http://dev.physicslab.org/Document.aspx?doctype=3&filename=Electrostatics_ContinuousChargedRod.xml. *Q8* Source: http://faculty.spokenfalls.edu/InetShare/AutoWebs/miker/Physics%20202/Chapt%2027,2/27_WorkBookSolutions.pdf

'N' to change the charge of the test point charge from positive to negative. How does the force change?

Learning perceptions, usability and ease of use survey

At the end of the laboratory report students were provided with a survey where they were prompted to report their perceptions about the learning experience. The survey consisted of an open-ended question and five Likert-scale questions where students reported their level of agreement (strongly agree, agree, undecided, disagree and strongly disagree) with the following statements: (1) I enjoyed learning physics concepts with haptic devices; (2) Haptic devices were easy to interact with; (3) The force feedback was easy to be interpreted; (4) Interacting with haptic devices requires a lot of mental effort; and (5) Interpreting the force feedback requires a lot of mental effort.

Data analysis method

The conceptual learning assessment was analyzed using both descriptive and inferential statistics. The hypothesis was that all participants would gain a significant conceptual learning about the electric fields for distributed charges after being exposed to the visuohaptic simulations. This gain was hypothesized in the form of improved test scores comparing the pre-intervention assessment of conceptual knowledge and a post-intervention assessment of the same knowledge. During the descriptive analysis, mean scores and standard deviations were calculated for pretest and posttest scores. The scores from the pretest and posttest were graded as (0) incorrect (1) correct for multiple-choice questions 1 to 8. Question 9 was scored as (0) incorrect or no answer, (1) partially correct if the student was able to represent the forces inside or outside of the ring charge, or (2) correct if students properly draw forces inside and outside of the ring charge. Analyses were performed for pretest-posttest scores and for questions regarding each charge distribution, Q1 to Q9. The coded data were then analyzed using inferential statistics using a paired *t*-test to check if there were any conceptual gains because of the visuohaptic intervention. Cohen's d-test (Cohen, 1988) was used to compute the effect size of the visuohaptic intervention. The following scale was used to interpret the effect size: (a) Weak effect size: $|d| < 0.2$; (b) Weak to moderate effect size: $0.2 < |d| < 0.4$; (c) Moderate effect size: $0.40 < |d| < 0.65$; (d) Moderate to strong effect size: $0.65 < |d| < 0.8$; (e) Strong effect size: $0.8 < |d|$ (Rubin, 2012). Finally, students were divided into two groups: students with previous physics courses at the undergraduate level and students with no courses at the undergraduate level.

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

Students' perceptions of their use of haptic technologies for learning were gathered via a questionnaire. The comments reporting students' self-perceived benefit of the use of haptic devices for their learning were grouped into different categories namely positive, negative or suggestion-oriented. Corresponding to the different categories, further sub-categories were assigned based on the similarity of comments. These categories and sub-categories are different for the three charge distributions. Counts for each of the sub-categories were calculated and sample responses were documented corresponding to each of these sub-categories. Finally, students' perceptions of the usefulness, ease of use and mental effort were scored on a scale from 1 to 5 (1 = Strong Disagree, 2 = Disagree, 3 = Undecided, 4 = Agree, 5 = Strongly Agree) and average scores and standard deviations were calculated.

Validity and reliability

Content validity was performed by two experts in physics education, who reviewed the materials and provided revisions to the learning design, the simulation tools and assessment instruments. These materials were validated on content accuracy and correctness. On the basis of the evaluation by the experts, some items were revised in terms of wording to provide clarification. The experts also validated the appropriateness of the

Table 2 Scoring rubric for the Force feedback interpretation questions

Configuration/ Explanation	No explanations or misconceptions (0)	Identifies a connection, but it is either incorrect or incoherent (0.5)	Correctly identifies all the relevant components (1)
Point (P)	No answers or answers contain misconceptions.	Student interprets the force feedback in the context of visualization as not proportional.	Point charge exerts a greater force when closer to it than farther.
Line (L)	No answers or answers contain misconceptions.	Student interprets the force feedback in the context of visualization as not proportional. Student identifies individual scenarios, but does not interpret the difference correctly.	Line charge exerts greater force when close to the line, but the force decreases inversely proportional to distance as you move away from the charge.
Ring (R)	No answers or answers contain misconceptions.	Student interprets the force feedback in the context of visualization as not proportional Student thinks that force at center and away from ring is the same.	The force is zero at the center, increases from the center to the circumference and decreases outside the ring.

topics and questions targeted, as well as the alignment of the assessment materials with the technology and other learning materials.

In addition, a pilot study of all data collection instruments, procedures, and learning materials was performed with 19 undergraduate engineering students during an informal training session. Eighteen students reported having some background in physics, while only one student had no background in physics. Similarly, four students reported having taken a course in electricity and magnetism the previous semester. During the pilot study we also explored motivational and usability factors, as well as level of mental effort associated with using haptic technology for learning.

Results from the pilot study suggested that overall, students from all backgrounds performed moderately low in the pretest assessment having approximately half of the questions correct. Considering the descriptive statistics from the posttest measures, it can be identified that students improved their performance to an acceptable level (~60%). The Cohen's effect size value ($d = -0.455$) suggests a moderate conceptual gain. Evaluation of the laboratory report suggested that, in general, students were able to make appropriate mappings between the force feedback received by the haptic and the conceptual interpretation of the force contextualized in the visualization.

Students' perceptions of their learning experience were collected with a final open-ended question. Eighteen responses received were then categorized based on similar answers. Three types of responses were identified; responses that commented on (a) the usefulness of the learning experience (27%) with comments such as "Very helpful for understanding physics concepts;" (b) finding the experience as very interesting (27%) with comments such as "Very interesting demonstrating physics concepts;" and (c) enjoyment of the learning experience (17%) with comments such as "It was quite fun!" Two types of negative responses were identified: (a) other educational methods as being better (17%), and (b) other comment such as the need of higher fidelity of the visualization component, or finding the haptic component as distracting (12%).

Results

Our results are presented in three main sections: (1) students' gains in conceptual learning derived from the assessment of pretest and posttest grades, (2) students' interpretation of the force feedback obtained from their qualitative responses in the laboratory report, and (3) students' perceived learning afforded by the haptic learning experience. Finally, the last section reports usability considerations.

Conceptual learning

The results from this section aim to address the research question: Can technology undergraduate students (with varying physics backgrounds) improve their conceptual understanding about electric fields for distributed charges after a guided exploration with visuohaptic simulations? Student conceptual learning was obtained from the evaluation of pretest and posttest grades. Questions were grouped into five categories: total score (Questions 1 to 9), general understanding (Questions 1 and 8), point charge (Questions 3 and 4), line charge (Questions 5 and 6) and ring charge (Questions 7, 8 and 9).

The p-value for the total score, general, point charge, line charge and ring charge is less than 0.05 (Table 3), indicating a significant increase in the students' conceptual understanding about these categories. Results from the pretest measures suggest that overall, students from all conditions performed moderately low, having approximately half of the questions correct. Considering the descriptive statistics from the posttest measures, it can be identified that students improved their performance to an acceptable level (~70%). The Cohen's effect size value ($d = -0.94$) suggests a strong conceptual gain on the total score. Table 3 below depicts a summary of the inferential and descriptive statistics of student conceptual learning.

In order to identify the effect of prior instruction, two groups of students were created based on their previous exposure to physics courses. Twenty-two students had taken one or more undergraduate level physics courses. The courses included a combination of topics such as: (a) electricity, light, and modern physics, for students not specializing in physics; (b) mechanics, heat, and sound, for students not specializing in physics; or (c) electricity, magnetism, light, and modern physics for technology students.

Eight students had not taken any physics courses at undergraduate level and were just exposed to a high school level physics background. The twenty-two and the eight students were separated into two groups for further investigating the level of gain in the conceptual understanding of both these groups. As shown in Table 4, on the average the twenty-two students with an undergraduate level physics background scored around 56% of total score in the pretest assessment, and improved their conceptual understanding significantly ($p = 0.006$) reflected by the increase of the posttest scores to approximately 68%. On the other hand, the remaining eight students with only high-school level physics background started with approximately 43% of the total score in the pretest and improved their posttest scores significantly ($p = 0.003$) to approximately 76%. We also statistically compared learning gains from both groups using a t-test and identified that students with only high school physics background significantly outperformed students who were previously exposed to college-level physics courses ($p = 0.0286$).

Interpretation of the force feedback

This section addresses the research question: How are students making meaning of the force feedback in the context of the visualization? A particular question designed to evaluate students' appropriate interpretation of the force feedback was Q9. It was

Table 3 Descriptive and inferential statistics of student conceptual learning

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

Table 4 Descriptive and inferential statistics of students exposed to only high-school physics courses and students with undergraduate physics courses

	Pretest		Posttest		Gain = posttest − pretest		
Category	Mean	Std. dev.	Mean	Std. dev.	Mean gain	t	*p*-value
Undergraduate-physics (*n* = 22)	5.59	2.08	6.82	1.79	1.22	3.029	0.006
High-school physics (*n* = 8)	4.25	1.75	7.62	1.68	3.37	4.473	0.003

observed that students experienced a significant improvement in their representations of the spatial distribution of the electric field. The question required students to plot the direction of the electric field both inside and outside the positively charged ring. Analyzing the pretest scores, only 16% of the students were able to correctly plot the direction of the electric field. However, the analysis of the posttest scores revealed that this percentage increased to 84%. These results suggest that students were able to properly interpret the force feedback afforded by the haptic device.

The pretest and posttest attempt for Q9 for one particular student is shown as an example in Fig. 8. In the pretest attempt, the student had no understanding about the direction of the forces. However, in the posttest attempt the student was able to correctly plot the direction of the forces, both inside and outside the ring. Similarly, a second student (Fig. 9) initially plotted incorrect directions both inside and outside the ring in the pretest. After the visuohaptic intervention, the student was able to correctly plot the directions.

Written responses from the laboratory report were also used to identify how students made meaning of the force feedback. After scoring students' responses with a rubric, results suggest that, in general, students were able to make appropriate mappings between the force feedback received by the haptic and the conceptual interpretation of the force contextualized in the visualization. The results from the lab report evaluations also suggest a greater number of students reporting a complete understanding in the point charge as compared to the line charge and ring charge simulation. However, students were not able to clearly explain how the force changed as they moved the test charge from the center of the ring to its inside circumference, or away from the outside circumference. Table 5 summarizes student level of achievement on the laboratory report.

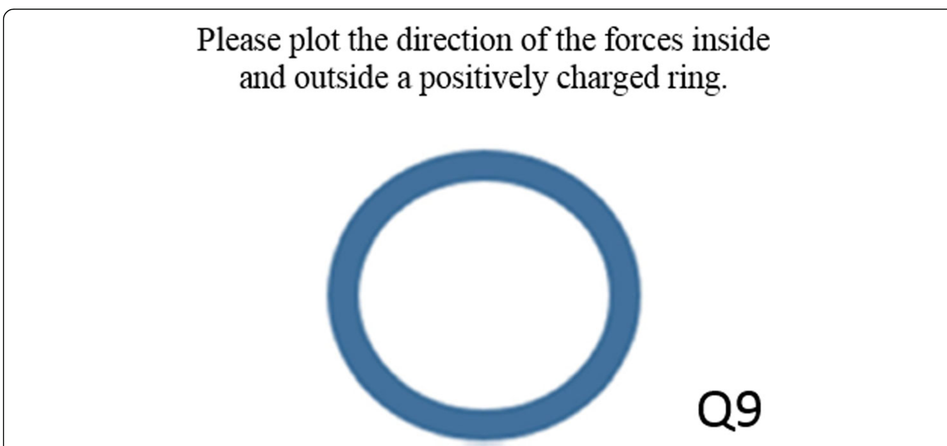

Fig. 7 Question about the direction of the forces for a positively charged ring. *Q9* Source: Question developed by the researchers

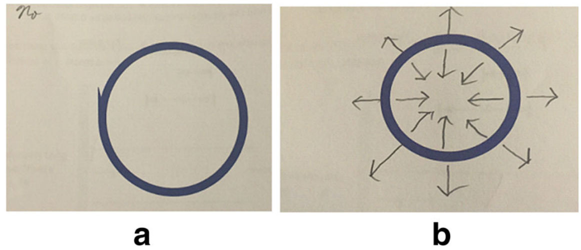

Fig. 8 Sample of a student's response from no understanding to a correct understanding. **a** Pre-test. **b** Post-test

Learning perceptions, usability and ease of use

The first part of this section addresses the research question: What are students' learning perceptions after using the visuohaptic simulations in order to understand the concepts of electric fields produced by distributed charges? Students were asked for feedback about their learning experience with haptic technology in the last section of the lab report. Students' perceptions of their learning experience were obtained with a final open-ended question. Twenty-nine responses received were then categorized based on their similarity. Three types of responses were identified, commenting on: (a) the usefulness of the learning experience, (b) finding the experience as very interesting, and (c) enjoyment of the learning experience. Two types of improvement-oriented responses were identified: (a) suggesting improvements in existing simulations, and (b) other comments such as the need of higher fidelity of the visualization component, or finding issues in the way the device works.

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

The second part of this section addresses the following research question: What are students' perceived usefulness and ease of use of haptic technology for learning? As it will be presented next, our findings show that students' perceptions of the learning experience in terms of usefulness, ease of use and mental effort were overall positive. The student responses to the survey questions were graded on a scale of 1 to 5 (1 = Strong Disagree, 2 = Disagree, 3 = Undecided, 4 = Agree, 5 = Strongly Agree). A summary of the descriptive statistics is presented in Table 7.

Findings from Table 7 suggest that students agreed that they enjoyed using the haptics device for learning and the technology was easy to interact with. On average, the students agreed that they enjoyed learning physics with haptic devices, haptic devices were easy to use and the force feedback was easy to be interpreted. Also, they

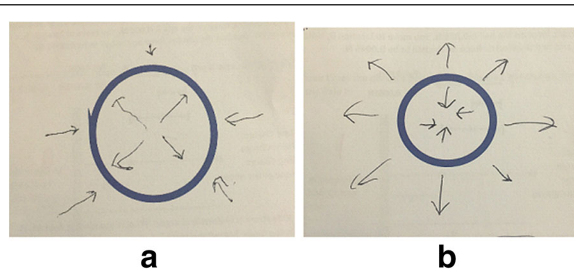

Fig. 9 Sample of a student's response from an incorrect understanding to a correct understanding. **a** Pre-test. **b** Post-test

Table 5 Descriptive statistics of student performance on the laboratory report

Force feedback awareness and mapping from visualization			
Configuration	Point charge	Line charge	Ring charge
Mean	0.92	0.8	0.7
Std. Dev.	0.19	0.19	0.25
Count of 0	0	0	0
Count of 0.5	5	12	18
Count of 1	25	18	13

unanimously disagreed that interacting with haptic devices or interpreting force feedback required a lot of mental effort.

Discussion

Our results suggest that overall students significantly improved their conceptual understanding about electric fields for distributed charges after being exposed to a visuohaptic simulation guided activity. Principles suggested by the CATLM framework helped students to overcome some of the challenges previously identified, such as students experiencing a split attention effect and as a result cognitive overload (Sanchez et al., 2013), when adding the sense of touch to a multimedia learning experience. We hypothesized that CATLM principles scaffold the learning experience in the following ways. First, the pre-training session was introduced in order to diminish a possible split-attention effect. Then, the guided activity helped students to sequence and at the same time self-pace the instruction by guiding the learner one step at a time. These principles already showed some promise, where learners in a visuohaptic simulation group outperformed learners in a visual-only group, as well as learners in an instructional module group, although not significantly (Magana et al., 2017). We therefore deemed necessary to look deeper into students' interactions by guiding the activity and stimulating students to reflect throughout the learning process at the same time. To

Table 6 Categories and percentage of responses about learning perceptions

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

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

Question	Mean	Std. Dev.
I enjoyed learning physics concepts with haptic devices	4.53	0.51
Haptic devices were easy to interact with	4.50	0.51
The force feedback was easy to be interpreted	4.47	0.68
Interacting with haptic devices requires a lot of mental effort	1.90	0.55
Interpreting the force feedback requires a lot of mental effort	2.10	0.84

this end, the guided activity prompted students to reflect on their own interpretations of the force feedback. That is, specific questions in the assignment asked students to think through the force feedback, and interpret that feeling in the context of the visualization. It seems that this approach helped students to focus on their sense of touch and were able to conceptualize the force feedback. Results from the second research question support this claim. For instance, the majority of the students initially plotted incorrect directions both inside and outside the ring in the pretest, and then, after being exposed to the visuohaptic intervention, the majority of them were able to correctly plot the directions. Similarly, written responses on the laboratory report suggest that in general, students were able to make appropriate mappings between the force feedback received by the haptic and the conceptual interpretation of the force contextualized in the visualization, although challenges still remain. There are several avenues for future work and specific challenges that need further exploration include differences in students' learning gains within configurations. A greater number of students demonstrated higher understanding of the point charge as compared to the line charge and ring charge simulations. Specifically, students were not able to clearly explain how the force changed as they moved the test charge from the center of the ring to its inside circumference, or away from the outside circumference. Moreover, better interaction strategies and support are needed in order to help students make meaning of this phenomenon.

A second key finding of this study relates to student learning gains when divided by their previous physics coursework. From the 30 students who participated in the study, about one third of them were just exposed to high school level physics and not to college level physics courses at the time of the study. Students with high school-only physics background significantly outperformed students who have been previously exposed to college-level physics courses 8% higher in the posttest average score. Other studies have identified similar results; for example, Young et al. (2011) identified that the addition of haptic feedback did not result in statistically significant learning differences between students in the experimental group and the control group in a study that explored elementary school students understanding of buoyancy. They did identify, however, that younger learners (i.e., fourth graders), were able to learn as much as older learners (i.e., sixth graders). Similarly, Minogue, Jones, Broadwell, and Oppewall (2006) conducted a study with 80 middle school students where they compared the effectiveness of visual and haptic feedback plus visual simulations to help students understand concepts of cell biology. Although overall findings from their study suggested that the addition of haptic feedback did not result in statistically significant learning differences, Minogue et al. (2006) identified that the addition of the haptic feedback had a positive impact on the low-achieving students' ability to answer one particular question. More research studies, preferably qualitative studies that identify how students engage cognitively when they interact with visuohaptic simulations, are needed to further explain this result.

Finally, students overall agreed that they enjoyed using the haptic device for learning and found the technology as easy to interact with. On average, the students agreed that they enjoyed learning physics with haptic devices, haptic devices were easy to use and the force feedback was easy to be interpreted. Also, they unanimously disagreed that interacting with haptic devices or interpreting force feedback required a lot of mental effort. Also, as similar to other studies (i.e., Park et al., 2010), many students found the force feedback helpful in the learning process.

The implications for teaching and learning from this study relate to the affordances provided by haptic technologies to support student learning. Specifically, simulations combined with force feedback can add a whole new outlook towards education. Enhancing science visualizations with haptic feedback can have the potential not only to engage learners in meaning making with representations more deeply (e.g., Magana & Balachandran, 2017), but also to help them encode knowledge for future use. However, caution is needed in supporting students throughout the learning process in order to avoid cognitive overload. Instructors should include different pedagogical approaches and design principles that can help them to effectively use computer simulations for learning (Magana et al., 2017). In the present study CATLM principles were primarily used to guide and support the learning process when learning with visuohaptic simulations. We posited that incorporating haptic technology with computer simulations along with pedagogical and scaffolding principles would guide students to understand and encode knowledge. We believe that by guiding and prompting students to reflect throughout the learning process we can help them embed cognitive activity in the environment (a) by reducing cognitive load (Paas & Sweller, 2012), and (b) by internalizing sensorimotor routines derived from the perceptual and interactive nature of the manipulatives (i.e., Pouw, Van Gog, & Paas, 2014). As a result, forms of haptic perception through different forms of interaction, can promote embodied learning (Höst, Schönborn, & Lundin Palmerius, 2013).

Limitations, conclusion and future work

Although the results of this work are promising, the use of haptic technology for conceptual understanding by touch needs further investigation. We hypothesized that the force feedback component of haptic would contribute to an improved conceptual understanding of the fundamentals related to electric field for distributed charges. Our results support this expectation and we found that students improved their understanding of the concepts of electric fields for distributed charges as shown by the statistically significant increase from pretest to posttest scores. We attribute these changes to CATLM principles which directed the learning design. We believed that specifically the combination of guidance and reflection, helped students make explicit connections between the force feedback received and the visualization component of the depicted science concepts. Preliminary results from the current research showed significant positive results, but a more rigorous design with more students is still needed to validate the usefulness and advantage of using the haptic technology for creating a cognitive impact.

The present study poses several limitations. The laboratory session was not a part of the regular curriculum. The students participated to get either an extra credit or participated as a part of an additional assignment they had volunteered for. It is hard to judge if students put in their best efforts to perform well in the assessments associated with the study. Embedding the present study into an existing curriculum will probably yield more reliable results and observations. The present study did not evaluate the performance of the visual only scenario as a control group. Hence, it is difficult to differentiate how much students benefitted from the visual component and how much they benefitted from the haptic component. Since the present study was largely quantitative in nature, another aspect to explore would be a qualitative perspective to understand the students learning process with the visuohaptic simulations. Future work includes considering a qualitative approach to explore additional aspects of conceptual understanding using interview or think-out-loud protocols. Using a more open-ended approach will help to get deeper insights of the student's misconceptions and allow the researcher to follow the trail of thoughts of the learner. Ensuring that the haptic modality is given more focus in the instruction and assessment components will be an important aspect of the future work. Additionally, it would be important to identify different learning principles that strategize to integrate the sense of touch for learning different scientific concepts. The learning materials will also be enhanced to support constructivist-learning approaches with a focus on problem-based learning or inquiry-based learning strategies. Another interesting aspect to explore would be to calibrate different force feedbacks for different scenarios to enable students to certainly identify the dependence of the electric force with distance for the different charge configurations such as constant for plane charge, linear decrease for infinitely long line charge and quadratic decrease for point charge (Neri et al., 2015). Also, different tactile feedback stimulus patterns should be further explored by characterizing how distinctive tactile impressions (e.g., Nishino et al., 2013), can result in more meaningful interactions that conduct to learning and understanding. And last, but not least, another venue for possible future work would be the mapping of haptic feedback to other touch technologies for tablets or mobile devices (e.g., Zhou, Niibori, Okamoto, Kamada, & Yonekura, 2016), so simulations can be made more accessible to learners.

In conclusion, the potential educational use of haptic technology in science education is still in its infancy, and the evidence suggests that if used appropriately, it can have an enabling potential in supporting conceptual understanding. Further research is needed in this field to explore the different approaches of using haptic technology to enhance teaching and learning.

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Authors' contributions
US carried out the data collection, data analysis, and the interpretation of the results for the study. AM conceived the study and participated in its design, interpretation of findings, and coordination. BB supervised the design of the visuohaptic simulations. LN, DE and JN provided feedback in the design of the materials and interpretation of the findings. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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