

Article

Visuo-Haptic Simulations to Understand the Dependence of Electric Forces on Distance

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Abstract: In this paper, the potential of visuo-haptic simulators to help engineering students to understand the nature of electric forces between different electric charge distributions is addressed. Three visuo-haptic simulators were designed to perceive the attractive–repulsive behavior as well as the dependence on distance of electrical forces for: (a) point charge, (b) line charge, and (c) plane charge. Design elements were incorporated to improve the 3D perception of the simulators. A sample of $N = 111$ engineering students practiced with the simulators: 87 enrolled in an Electricity and Magnetism course and 24 enrolled in a more advanced Electromagnetic Fields course. Pre-test and Post-test were applied before and after working with the simulators and average learning gains were obtained. *t*-tests were performed to determine the statistical significance of the results. Significant learning gains were obtained for the comprehension of the force dependence in the case of line charge and plane charge, but not for the point charge, due to the fact that most students started with very high Pre-test scores in this last case. These results suggest that the use of visuo-haptic simulators may help students to better identify the dependence of electric forces on distance. It was also observed that the potential effect of improving the recognition of electric interactions was higher among students with lower previous familiarity with these topics, as compared to more advanced students. Through exit surveys, it was found that the students liked very much the haptic activity and that it sparked their interest in learning new physical concepts.

Keywords: visuo-haptic simulation; higher education; education innovation; learning gains; engineering education; physics and engineering

1. Introduction

Advances in multimodal interaction have enriched teaching-learning models. The theory of embodied cognition is based on the paradigm of adding senses, improving the learning experience, and allowing the student to acquire knowledge on a deeper and longer-term level [1]. Haptic technologies add the sense of touch in a virtual world, allowing users to perceive different sensations such as hardness, shape, weight, and texture of virtual objects in visuo-haptic simulators [2,3].

Visuo-haptic learning environments allow the student's brain to receive stimuli from different channels, allowing a more complete experience and better acquisition of concepts and experience in the learning process [4]. Haptic devices recreate the sense of touch by computing interactions between the user and virtual objects, rendering force feedback on the user. Visuo-haptic environments that use low-cost haptics open up the possibility of using them both at home and in

educational spaces This technology has enabled the development and creation of novel interactive applications (Figure 1).

Among other applications, visual technologies coupled with haptic devices have gained attention in Physics teaching due to their potential application to help understand the nature of different kinds of forces that appear in physical scenarios [5–9]. In particular, the usefulness of visuo-haptic implementations to sense those forces that cannot be tested manually have been explored, as the case for example of the electromagnetic forces, for which only indirect measures can be inferred from laboratory experiments. Several researches have been conducted with this purpose [10–15].

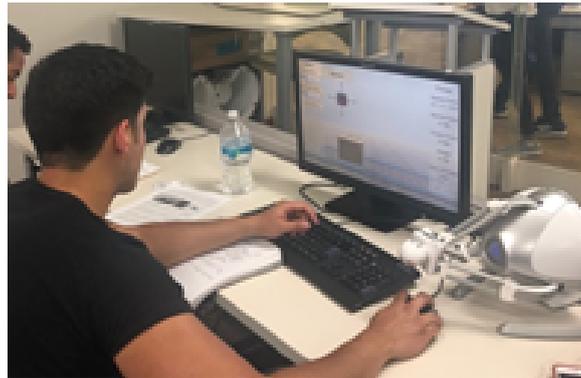


Figure 1. User interacting with a visuo-haptic simulator.

In engineering education two of the basic key areas are Classical Mechanics and Electricity and Magnetism. In Classical Mechanics several visuo-haptic simulators have been proposed for better understanding the operation of simple machines [5,13], gears [6], and the nature of friction forces [7,8,13,16,17], among other topics. Whereas Classical Mechanics deals mainly with tangible concepts, Electricity and Magnetism studies mostly abstract ones. For example, in the case of electrical forces between charge distributions, the student requires a lot of imagination to understand the essence of some interactions and the underlying physical concepts. It has been identified that undergraduate students often find Electricity and Magnetism ideas difficult and confusing [18]. Some of the main deficiencies are related to misconceptions of Maxwell's equations as well as misunderstandings between electric fields and their sources. Consequently, related problem-solving is troublesome [19]. Specifically, it has been reported that students have difficulty with electromagnetic induction, electric potential, and electric potential energy [20]. In this regard, the design and implementation of carefully designed visuo-haptic scenarios to help understand the nature of electromagnetic interactions can be suitable for the formation of engineering students.

One important issue regarding the design of visuo-haptic simulators in Physics is the assessment of their impact on students' learning [6,7]. Several studies suggest that statistically significant learning gains can be achieved when properly designed scenarios, combined with appropriate setups and guided experiments, are implemented [9,15,16]. Nevertheless, the need for further investigation to find optimal practices aimed to obtain improved student learning is still required.

Therefore, the aim of this work is: (i) to present the design of three visuo-haptic simulators to study the nature of electric forces, (ii) to prove their implementation with engineering students, and (iii) to assess their impact on student learning and student perception. The layout of this paper is as follows. In Section 2, the related work is briefly outlined. In Section 3, the methodology followed in this research is presented. Section 4 is dedicated to data analysis and results. Section 5 includes a discussion of the main results. Finally, in Section 6 the main conclusions and future work are presented.

2. Related Work

In recent years, TICs have focused on education to improve and update knowledge and skills acquisition in different areas. In STEM, E-learning courses and Technology-Enhanced Learning

(TEL) practices have started to be applied in courses to improve or complement classes [21,22]. Computer applications and systems have experienced exponential growth in the creation of simulators and learning stations, and nowadays they are a feasible and novel solution to improve learning and training [22]. The current trend focuses on the addition of haptic devices to simulators to provide force feedback [12–14]. In the area of Electricity and Magnetism, virtual simulators have also been studied in recent years. Park et al. developed a visuo-haptic simulation to teach physics concepts related to the learning of nanotechnology [23]. They implemented various simulations of point charges and their interactions aimed to improve student learning. A control study was performed to assess the impact on their learning. Half of the participants used three visuo-haptic simulations while the others were assigned to an only-visual one. Moreover, Dega et al. performed a study to assess students' conceptual change in electricity and magnetism using simulations [20]. The authors used simulations to situate interactive engagements and to explicit visual representations regarding students' learning of these concepts. Moreover, they performed a modified diagnostic exam of Electricity and Magnetism to assess the impact of their approach. Results indicate that there is a statistically significant difference in students' conceptions of electromagnetism concepts.

As technology progresses, the current trend in teaching simulators is the addition of haptic devices in simulators to also provide force feedback [3,24,25]. Recent visuo-haptic simulators for Electricity and Magnetism have concentrated on helping students to determine the direction of the electric/magnetic forces to infer the corresponding geometry of the electric/magnetic fields [14]. Sanchez et al. created a haptic simulation to teach freshmen engineering students about electromagnetism [12]. The aim of their study was to examine the efficacy of these simulations in the students' learning process. The authors performed a quasi-experimental experiment where students were divided into two groups, one where the participants used visual-only simulations and the other where their visuo-haptic simulation was used. Sanchez et al. found that the group that used the visuo-haptic simulation had a more positive conclusion and understanding of the task than those who only used the visual representation.

On the other hand, Magana et al. developed three 3D simulators to enhance the understanding of how charges interact with different force fields. They have incorporated multimedia principles for supporting the conceptual learning of electricity and magnetism to design their visuo-haptic simulators for different charge distributions [26]. Students were able to increase their knowledge regarding the direction of the electric field around charge distributions. Results from this study suggest that students significantly improved their conceptual understanding of electric field interactions for distributed charges after being exposed to a visuo-haptic simulation guided activity. Although they found promising results in terms of conceptual learning gains determined from the comparison of pre-test and post-tests, on the one hand, and very positive students' perceptions on the use of their simulators, on the other, they mention that more studies of the impact of visuo-haptic simulators to understand the nature of electric and magnetic interactions are still needed. Among different possible research lines, Magana et al. point that an interesting aspect to explore would be the force calibration for different charge distributions.

Recent visuo-haptic simulators for Electricity and Magnetism have concentrated on helping students to determine the direction of the electric/magnetic forces to infer the corresponding geometry of electric/magnetic fields. Hamza-Lup and Goldbach presented a game scenario in which the student can move a charged particle through an electromagnetic field to *feel* the Lorentz force exerted on it in order to test the direction of the vector-cross product between the charge velocity and the magnetic field [15]. The results of this research suggest that the appropriate design of visual-haptic interfaces to present abstract concepts promotes a greater commitment among students and therefore greater learning can be achieved.

In this regard, Neri et al. [13] and García-Castelán et al. [27] have performed preliminary studies of the understanding of the dependence of the electric force with distance for three charge distributions: point charge, line charge, and plane charge, which have $1/r^2$, $1/r$ and constant distance dependencies,

respectively. Students were able to test with the haptic device the force strength at different distances from each of these charge distributions, and these authors reported an interesting trend of increasing students' learning gains on their recognition of the distance dependence through the comparison of post and pre-test grades. Nevertheless, they also pointed out that their findings were still not statistically significant and that future studies with larger student samples should be performed to further assess the impact of the simulators on increasing student learning. Given the fact that typical electricity and magnetism graphical displays of the visuo-haptic simulators presented in the literature are usually displayed in two dimensions, it has also been suggested the design of appropriate 3D graphical displays for these simulators to improve the depth perception, which is important to recognize the spatial behavior of the electromagnetic forces and to better engage students [13–15].

Therefore, considering the previous arguments and continuing the work described in [13,27], a new study of the distance dependence of the electric force produced by different charge distributions is presented. The main purpose is that students perceive and quantify the behavior of the electric force with distance for these charge distributions. The proposed visuo-haptic simulators incorporate (i) a novel 3D graphical display for the visuo-haptic simulators aimed to better perceive the 3D dimension (depth), where the student can adjust the viewing perspective, and (ii) a larger student sample compared to those included in the preliminary works. Therefore, in this research, three visuo-haptic simulators for the sake of understanding the nature of electric forces produced by different charge distributions were implemented: (a) point charge, (b) line charge, and (c) plane charge. In particular, we were interested in exploring whether the simulators can help students to distinguish the dependence on distance of the electric forces exerted by each charge distribution on a point charge.

3. Methodology

The main objective of this work is to assess to what extent the use of visuo-haptic simulators can help students better understand the differences in the dependence with distance of the electric force between a point charge and different charge distributions. Therefore, in this quasi-experimental study, we investigated how to improve the spatial visualization of the electric force using Unity software, the *HaDIU* architecture [28] and an Electricity and Magnetism visuo-haptic environment designed *ad hoc*. The background programming of the simulators allows the students to feel the force variation as the distance between the charge distributions changes, and aided with the display of the actual magnitudes of the forces at a given distance, the students may be able to disentangle the dependence on distance of the electric force. Specifically, we investigated whether the use of haptic devices coupled with appropriate 3D visualizations can help students to understand the attractive or repulsive nature of the electric forces produced by different charge distributions, on the one hand, and the dependence on distance of these electric forces, on the other. Learning gains were derived to determine if they are statistically significant. Additionally, perception questionnaires were implemented to find out the opinions of the students about the use of the visuo-haptic simulators. The overview of our method is shown in Figure 2.

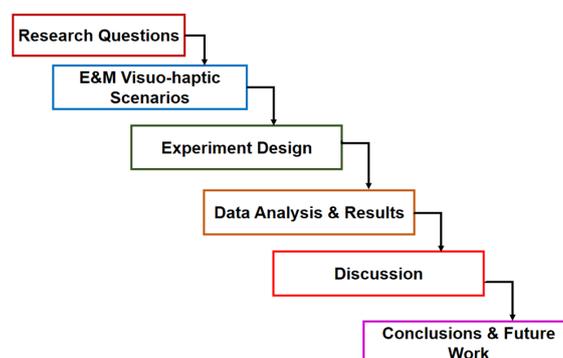


Figure 2. Overview of the methodology followed in this work.

3.1. Research Hypotheses

The research hypotheses that guide the present work are the following:

- (1) The use of haptic devices coupled with appropriate 3D visualizations may help students:
 - (a) to recognize the attractive or repulsive nature of electric forces depending on the sign of the electric charge distributions,
 - (b) to distinguish the distance dependence of the magnitude of the electric force exerted on a point charge by different charge distributions.
- (2) The student's perception of the use of visuo-haptic simulators to understand the nature of electrostatic interactions is positive and their use may increase the student interest in discovering new physical phenomena.

3.2. Design of Electric Force Visuo-Haptic Scenarios

Care was taken to provide an appropriate 3D visualization for the visuo-haptic simulators. The increment or decrement of the object sizes according to their depth position was incorporated. Guiding lines to show the 3D position of the test point charge were included. The corresponding Cartesian coordinates and the radial distance to the charge were also displayed on the screen. In addition, the possibility of changing dynamically the coordinate axes and the perspective angle of the viewer was also incorporated into the simulators to provide the best 3D visualization.

3.2.1. Haptic Devices and Technical Requirements

The visuo-haptic simulators were developed in Unity, using an in-house haptic device integration plugin "HadiU" [28]. The implementation allows for the use of a Geomagic Touch or Novint Falcon haptic device. All simulations were executed on computers equipped with Intel Xeon E5507 processor with 8 GB RAM, and Windows 1064 bits operating system. The user testing process was performed by using the workstations and a Novint Falcon haptic device connected to each computer. The simulators were developed as 3D environments due to the nature of their interaction forces, as can be seen in Figures 3–5.

3.2.2. Visuo-Haptic Scenarios

Three visuo-haptic scenarios were designed: (i) point charge, (ii) line charge, and (iii) plane charge.

- (i) **Point charge.** The goal of this simulator is that the student identifies the dependence of the electric force between two-point charges as a function of their magnitude, sign, and distance. In Figure 3, a screenshot of the simulator is shown. The user will feel the force strength between a charge Q_1 fixed at the coordinate origin and another charge Q_2 that can be manipulated with the haptic device. The signs and magnitudes of both charges can be changed.

Positive charges are shown in red color while negative ones are shown in blue. The magnitudes of the electrical charges (in μC) can be selected with a sliding bar or entering them directly. The electric force that Q_1 exerts on Q_2 is represented by an arrow. The user can explore the changes of the feedback force on Q_2 by approaching or moving Q_2 away from Q_1 . The screen displays the coordinates of Q_2 , its distance to Q_1 , and the components of the electric force. It is worth noting that the length of the displayed force arrow corresponds to the actual magnitude of the force which is calibrated in this case under a $1/r^2$ law. The electric force on Q_2 exerted by Q_1 is given by the Equation (1).

$$\vec{F} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} \hat{r} \quad (1)$$

where ϵ_0 is the electric permittivity of free space, r is the distance between the charges, and \hat{r} is the unit vector connecting the two charges.

- (ii) **Line charge.** The goal of this simulator is that the student recognizes the dependence of the electric force exerted by a very long, straight-line charge distribution on a point charge, as a function of the linear charge density of the line λ , the magnitude of the point charge Q , their signs, and the distance between them. Figure 4 presents a screenshot of this visuo-haptic simulator. The line charge is fixed along the vertical axis. The user can manipulate the position of the point charge Q with the haptic device, and the signs and values of λ and Q can also be varied. As before, positive charges are shown in red color while negative ones are shown in blue. The magnitudes of the point electric charge (in μC) and of the linear charge (in $\mu\text{C}/\text{m}$) can be selected with a sliding bar or entering them directly. An arrow drawn on Q shows the magnitude and direction of the force acting on it. The screen also displays the coordinates of charge Q , its radial distance to the line, and the components and magnitude of the electric force on Q . The length of the displayed arrow for this scenario is proportional to its actual magnitude as returned by the haptic device, according to a programmed $1/r$ inverse law. The electric force on Q exerted by the line charge is given by Equation (2).

$$\vec{F} = \frac{\lambda Q}{2\pi\epsilon_0 r} \hat{r} \quad (2)$$

where ϵ_0 is the electric permittivity of free space, r is the radial distance between the line charge and the point charge, and \hat{r} is the corresponding unit vector in the radial direction.

- (iii) **Plane charge.** The goal of this simulator is that the student tests the dependence of the electric force exerted by an infinite charged plane on a point charge as a function of the plane surface charge density σ , the charge magnitude Q , their signs, and the distance between them. Figure 5 shows a setup of the haptic device and the visuo-haptic simulator. The flat infinite plane charge is fixed to the YZ plane. The user can manipulate the point charge Q with the haptic device and feel the force acting on it. The signs and values of σ and Q can be varied and an arrow shows the magnitude and direction of the electric force exerted on Q . Positive charges are shown in red while negative ones are shown in blue. The magnitudes of the point charge (in μC) and of the plane charge (in $\mu\text{C}/\text{m}^2$) can be selected by a sliding bar or entering them directly on an active field on the screen.

The screen displays the coordinates of the point charge, its distance to the infinite plane, the components of the electric force exerted on the point charge, and the magnitude of the electric force. The electric force on the point charge exerted by the plane charge is given by Equation (3).

$$\vec{F} = \frac{\sigma Q}{2\epsilon_0} \hat{n} \quad (3)$$

where ϵ_0 is the electric permittivity of free space and \hat{n} is a unit vector perpendicular to the plane. Notice that the electric force is constant: it only depends on the surface charge density of the plane and the magnitude of the test charge, but it does not depend on the distance between the plane and the point charge.

3.2.3. Visual Display

Guiding lines were added to each simulator indicating the rectangular coordinates of the test point charge in order to help the student to better perceive its distance relative to each charge distribution in the 3D space (Figures 3–5). For the point charge simulator, a radial line connecting the test point charge to the fixed point charge was also added (Figure 3). In the case of the line charge simulator, a line indicating the radial distance of the test point charge to the line charge was also incorporated (Figure 4). In the case of the plane charge simulator, the distance of the test point charge to the fixed plane is given by the “ x ” coordinate of the test point charge (Figure 5).

The simulators also dynamically displayed the values of the rectangular coordinates of the test point charge and the corresponding relevant distance to each charge distribution. With the aim to help the student to better understand distance-dependence of the electric forces in each case, the rectangular

components of the electric force and its magnitude were also displayed in real-time on an output data box on the screen. Finally, in accordance with the needs of the experimental study, each scenario includes a button that displays an introduction to the task to help the student understand the aim of the activity using the simulator.

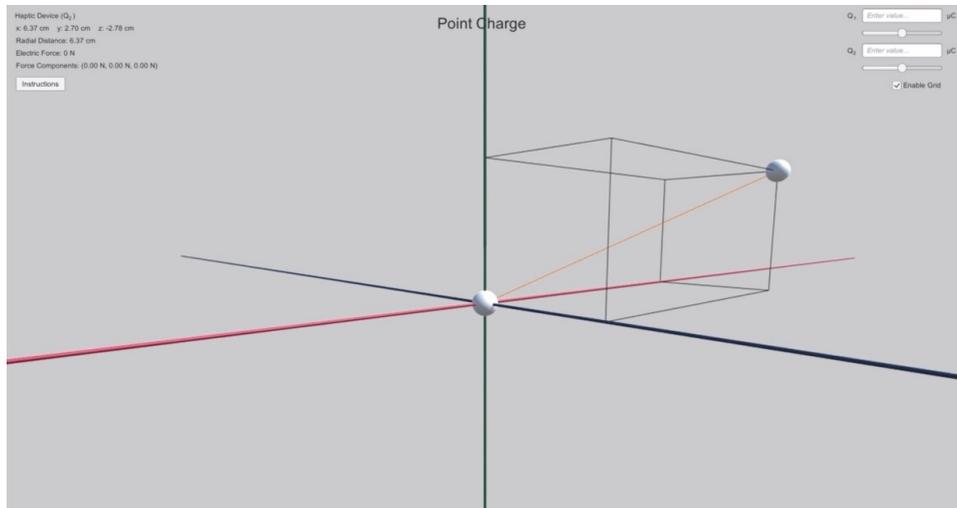


Figure 3. Two point charge visuo-haptic simulator.

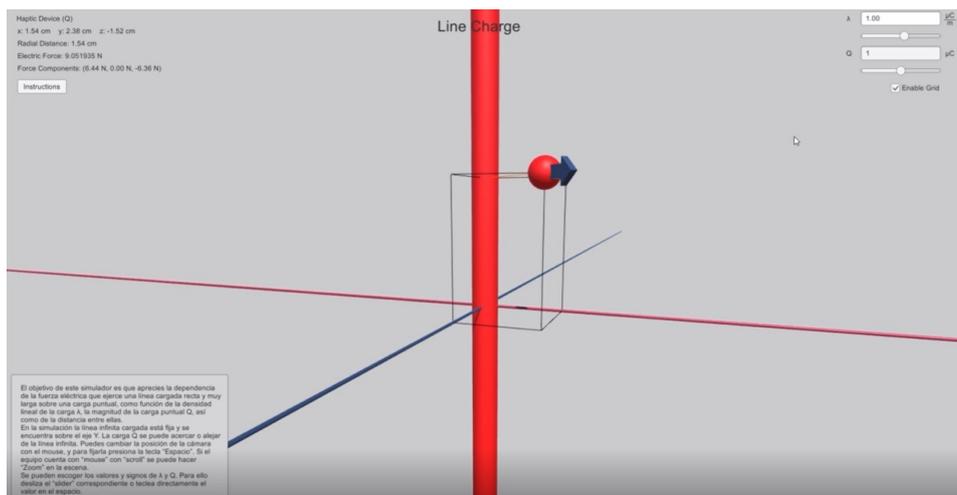


Figure 4. Line charge visuo-haptic simulator.

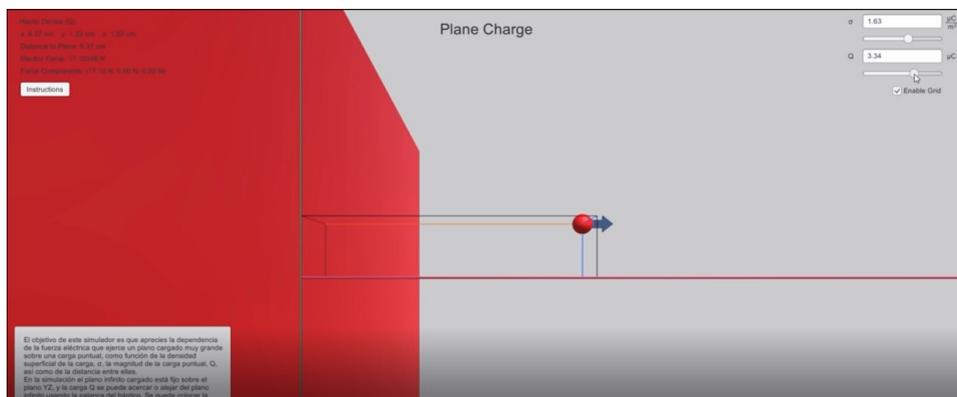


Figure 5. Plane charge visuo-haptic simulator.

3.2.4. Force Calibration

The force feedback of the visuo-haptic simulators was carefully calibrated to represent the theoretical behavior of the electric force for each charge distribution. For the point charge simulator, the force magnitude produced by the fixed charge on the test charge was adjusted to decrease as $1/r^2$; for instance, when doubling the distance, the haptic device rendered a force four times smaller in all directions from the fixed point charge. This behavior was preserved for all allowed ranges of the magnitudes of the fixed charge distributions and the movable test charges. This was also considered when their signs were changed to produce attractive or repulsive forces. In a similar way, for the line charge, the force on the test point charge was properly calibrated to reproduce the theoretical $1/r$ dependence for all radial distances to the line and allowed values for the linear charge density of the line or charge magnitude of the test charge, for both attractive and repulsive force cases. Finally, for the (infinite) plane charge simulator, the feedback force on the test point charge was set as a constant value regardless of its distance to the plane for given values and signs of the surface charge density and the charge magnitude of the test point charge.

It is important to notice here that the guiding lines added to the visualization coupled with the simultaneous force feedback given by the haptic device provide the student with an integrated visual-tactile perception of the electric force, according to embodied cognition theory [1,29].

3.3. Experiment Design

In the following section, a detailed description of the experiment design is provided.

3.3.1. Participants

A sample of $N = 111$ undergraduate engineering students at Tecnológico de Monterrey, Mexico City Campus, enrolled in four sections of an Electricity and Magnetism course (hereafter EM) and in one section of a relatively more advanced Electromagnetic Fields course (hereafter EF) used the visuo-haptic simulators. All students enrolled in these 5 sections participated in the study, as shown in Table 1. The Electricity and Magnetism course is given in the third semester of most engineering careers, while the Electromagnetic Fields course is given in the fifth semester of the Telecommunications and Electronic Systems (TES) engineering career. TES students do not take the EM course in their third semester but wait until their fifth semester to take the EF course. The overall thematic coverage of both EM and EF courses is similar; the main difference is that the EF course uses a more formal vector language to formulate Maxwell's equations along the course in both integral and differential forms, while the EM course focuses on the physical description of electric and magnetic phenomena and the differential form of Maxwell's equations is not addressed.

Table 1. Student sections who used the visuo-haptic simulators.

Section	Term	Subject	N
EM1	Aug–Dec 2018	EM	27
EM2	Jan–May 2019	EM	21
EM3	Jan–May 2019	EM	21
EM4	Jan–May 2020	EM	18
EF1	Aug–Dec 2019	EF	24
Total			111

3.3.2. Procedure

When the students work for the first time with haptic devices, they were intrigued by how they function and by the scenarios that appear on the screen. It is inevitable to explore haptic devices by excitingly moving the joystick. Teachers had to exert extreme care in instructing the students not to move the joystick abruptly since it can break down. The surprised faces of the students when

they feel the forces for the first time was fascinating. There was a sense of wonder that is priceless. In this way, haptic devices capture the attention of the students and engage them in the activity. This is when they began to connect the theory and what happens in the real world. This experience can never be completely achieved just by solving numerical problems. The haptic device experience fully complements the theoretical work, especially in courses such as Electricity and Magnetism, where abstract phenomena take place.

Due to the limited number of haptic devices in our Laboratory, the students were paired with a classmate to work on the electric activity in and out-of-class time. Due to space restrictions, only 6 couples were allowed per session. A timetable had to be planned and followed to receive all the participants in different slots during the week. Therefore, the completion of the implementation phase with our student sample took about two weeks.

The haptic activity took place as follows: A 5-question pre-test was applied to assess the students' prior knowledge about the attractive/repulsive nature and distance-dependence of electric forces for the charge distributions mentioned above (see Table 2). The pre-test took place in about 15–20 min. Then students were given some minutes to become familiar with the manipulation of the haptic devices before they could concentrate on the scenarios presented to them.

During the working sessions, students were given approximately one hour and a half to explore the three visuo-haptic scenarios (Figure 6). They were provided with a guide to perform several experiments with the simulators, in which they were asked to change the sign and magnitude of the charges and test the corresponding electrical force at different distances for each simulator. As an example, the instruction guide for the point charge simulator is included in Table 3. Similar guides were provided for the line charge and the plane charge simulators. As stated in the guides, for given signs and charge magnitudes, the students had to determine the corresponding relation between the electric force magnitude and distance. Besides feeling the magnitude of the electric force with the haptic device, the students recorded the data displayed by the simulator and were asked to plot them in order to help the students to better understand the different electric force-dependences in each case. The students were asked to prepare a report of the experiments. Some were able to complete it at the end of the experiments while others later turned it in to the teacher in class. As an example, in Figure 7, we present one of such graphs which helped the student to visualized the feedback force provided by the haptic device.

Table 2. Questions of the Pre-test and Post-test applied.

ID	Question
Q1	The electric force between point charges of the same sign is: (a) attractive (b) repulsive (c) depends on the values of the charges
Q2	The electric force between point charges of different sign is: (a) attractive (b) repulsive (c) depends on the values of the charges
Q3	The magnitude of the electric force between two point charges located at a given distance r is proportional to: (a) r^2 (b) r (c) does not depends on r (d) $1/r$ (e) $1/r^2$
Q4	The magnitude of the electric force between an infinite straight line charge and a point charge located at a given distance r is proportional to: (a) r^2 (b) r (c) does not depends on r (d) $1/r$ (e) $1/r^2$
Q5	The magnitude of the electric force between an infinite plane charge and a point charge located at a given distance r is proportional to: (a) r^2 (b) r (c) does not depends on r (d) $1/r$ (e) $1/r^2$

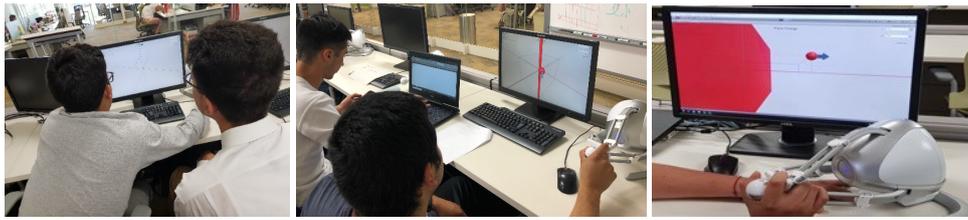


Figure 6. Students interacting with the visuo-haptic environments of electrical forces.

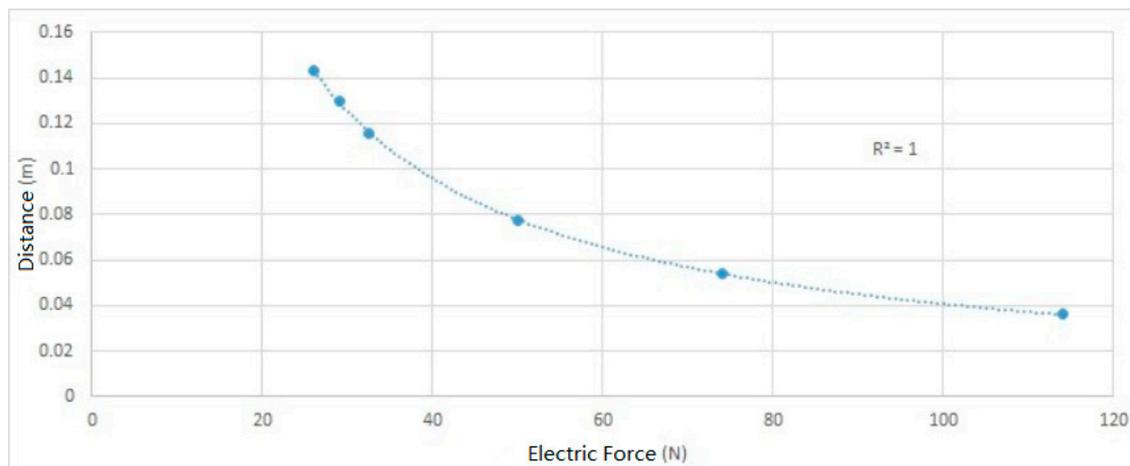


Figure 7. Example of a plot taken from a student’s final report illustrating the distance dependence of the electric force between a line charge and a point charge.

Table 3. Instruction guide for the point charge simulator.

Instructions

The goal of this simulator is to identify the dependence on the distance of the electric force between two point charges.

In the simulator, charge Q_1 is fixed at the coordinate origin. You can move closer or away charge Q_2 to feel the force (magnitude and direction) that charge Q_1 exerts on it, using the haptic joystick.

You can change the position of the camera with the mouse. To fix it press the “Space” key. You can also use the mouse to zoom in or out of the scene. You can choose both the sign and magnitude of each charge. Use the corresponding slider or directly type the value in the corresponding field.

What happens to the force between charges when you change their signs? When is it attractive or repulsive? What happens to the magnitude of the force when the values of the charges are changed?

On the screen, you can see the coordinates of Q_2 , its distance to Q_1 , the components of the force between the charges, as well as its magnitude. The charge color is red if it is positive (+) and blue if it is negative (-). The arrow indicates the direction of the electric force on charge Q_2 . Choose a set of values and signs for the point charges Q_1 and Q_2 and record the data. Move Q_2 near the edge of the screen and write down the value of the distance r between the charges, the magnitude of the force F on Q_2 , and the rectangular components F_x , F_y , and F_z of the force on Q_2 .

Repeat the process for another 5 distances approaching Q_2 to Q_1 . Make a table with these data and construct the graph of F vs. r . Fit a curve to your data. What is the dependency of F on r ? Write down your observations.

At the end of the activity and before students left the haptic device lab, a post-test identical to the pre-test was applied. Students were also given 15–20 min to solve the post-test. Both the pre-test and the post-test were graded on a 0 to 100 point scale, where each of the 5 questions was assigned 20 points.

3.3.3. Student’s Perception

After the post-test, a five-minute perception questionnaire was also applied to the students, before leaving the lab. This questionnaire was based on the one applied in the preliminary work by [13]. The questions asked on the survey are shown in Table 4, where (a), (b), and (c) refer to the point charge,

the line charge, and the plane charge simulators, respectively. A Likert scale was used as follows: 1 = Totally disagreement, 2 = Disagreement, 3 = Neutral, 4 = Agreement, and 5 = Total agreement.

Table 4. Questions of the exit perception survey.

ID	Question
QP1	I consider that the simulator (a,b,c) helped me to better understand the way in which electrical forces behave between a point charge and (a) another point-charge, (b) an infinite charged line and (c) an infinite charged plane.
QP2	I consider that the manipulation of the simulator (a,b,c) was simple and intuitive.
QP3	I consider that the visualization of the simulator (a,b,c) is appropriate and attractive.
QP4	I consider that overall, the visuo-haptic simulations helped me to better understand electric forces between charge systems.
QP5	I recommend to use visuo-haptic simulators to learn (a) other electricity and magnetism themes and (b) other Physics courses.

In the questionnaire, students were also allowed to freely comment on their experience with the visuo-haptic simulators and to mention other possible applications of the haptic technology. Once the students left the session, they all appreciated the effort of the academic team. Some students even came to ask when the next haptic activity was going to be held and even suggested other courses where they would like to have this kind of activities.

4. Data Analysis and Results

In the following section, the results of the present study are presented.

4.1. Learning Gains

A study of the students’ learning gains after working with the visuo-haptic scenarios was performed. Average students’ learning gains were calculated, using Equation (4), as the difference between the post-test and the pre-test average grades of each section and also for the entire student sample.

$$\langle G \rangle = \langle Post \rangle - \langle Pre \rangle \tag{4}$$

Relative learning gains were then also calculated using Equation (5) [30].

$$\langle G_{rel} \rangle = \frac{\langle Post \rangle - \langle Pre \rangle}{100 - \langle Pre \rangle} \tag{5}$$

This relation represents the fraction of the absolute learning gain relative to the maximum learning gain that can be attained. The results are presented in Table 5.

Table 5. Absolute and relative learning gains.

Section	N	Pre		Post		$\langle G \rangle$	$\langle G_{rel} \rangle$
		Mean	Std. Dev	Mean	Std. Dev		
EM1	27	69.6	15.1	85.2	17.2	15.6	0.512
EM2	21	77.1	20.3	88.6	18.0	11.4	0.500
EM3	21	74.3	15.7	87.6	11.8	13.3	0.519
EM4	18	72.2	15.6	82.2	15.2	10.0	0.360
EF1	24	95.0	12.2	96.7	11.3	1.67	0.333
Total sample	111	78.0	18.2	88.3	14.6	10.5	0.472

As it can be seen from Table 5, all EM sections obtained considerable absolute and relative learning gains. In Figure 8, a graphical comparison between the average pre-test and average post-test grades for the five sections indicated in Table 2 was made, considering the 5 questions mentioned above. In general, the average post-test is about 10 points higher than the average pre-test.

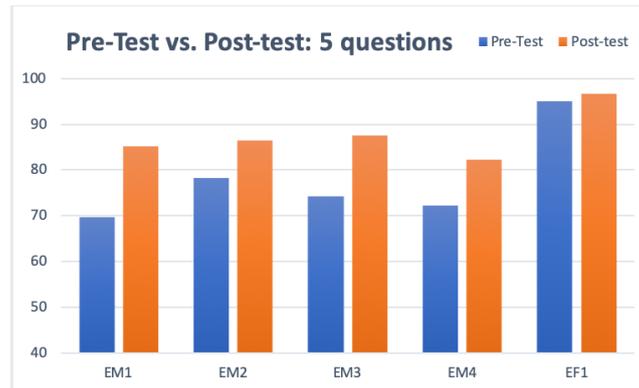


Figure 8. Comparison of average pre-test and average post-test grades for the five studied sections, considering the five questions mentioned in Table 2, in a scale 0–100.

A study of learning gains per question was also carried out for the total student sample. Each question was graded as 1 if the choice was correct or 0 if it was incorrect. Then the average grade per question was calculated for both the pre-test and post-test, and relative gains per question were then calculated. The corresponding results are presented in Table 6. Therefore, the relative learning gain was now calculated using Equation (6).

$$G_{rel} = \frac{Post - Pre}{1 - Pre} \tag{6}$$

where *Pre* and *Post* refer to the proportions of correct answers in each question.

Table 6. Question’s correct answers proportion, learning gains, and *Pre* vs *Post* comparison test (*N* = 111).

<i>N</i> = 111	Correct Answers Proportion		Gains		<i>t</i> -Test
	<i>Pre</i>	<i>Post</i>	<i>G</i>	<i>G_{rel}</i>	<i>p</i> -Value
Q1	1	1	0	-	-
Q2	1	1	0	-	-
Q3	0.847	0.802	−0.045	−0.053(*)	0.2952
Q4	0.441	0.631	0.190	0.340	0.0072
Q5	0.604	0.982	0.378	0.955	0.0000

(*) Calculated with Equation (7).

From Table 6, it can be seen that in questions Q1 and Q2 (attractive or repulsive nature of electric forces) the learning gains were zero. For questions Q4 (line charge simulator) and Q5 (plane charge simulator), the absolute and relative gains were very good, in particular for Q5, where the relative learning gain is very close to 1. On the other hand, a slight negative learning gain is observed for question Q3 regarding the distance dependence for point charges. Therefore, a relative learning loss was recalculated for Q3 with Equation (7). This represents the ratio between the average absolute learning loss and the maximum possible grade loss, the latter being the average pre-test value.

$$G_{rel} = \frac{Post - Pre}{Pre} \tag{7}$$

In Figure 9, the average pre-test and average post-test grades for the five sections indicated in Table 2 are presented, considering only questions Q3, Q4, and Q5 (Table 6), since for Q1 and Q2 the average leaning gains were zero. In this case, the average post-test is about 16 points higher than the average pre-test.

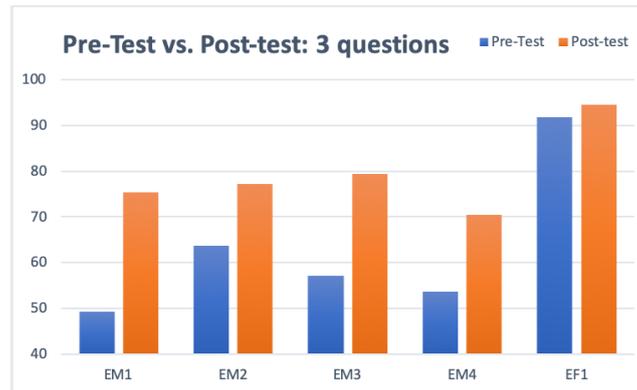


Figure 9. Comparison of average pre-test and average post-test grades for the five studied sections, considering only questions Q3, Q4, and Q5, in a scale 0–100.

In Figure 10, a comparison between the average pre-test and average post-test for the five sections indicated in Table 2, for each of the individual questions Q3 (blue), Q4 (orange), and Q5 (green), is presented. As can be seen, for question Q3 there is a slight decrease for sections EM1, EM3, and EF1, a slight increase for section EM4, and no change for section EM2. On the other hand, question Q4 presents increments for all sections, particularly for EM1 and EM4, and no change for EF1. Finally, Q5 shows important increments for all sections.

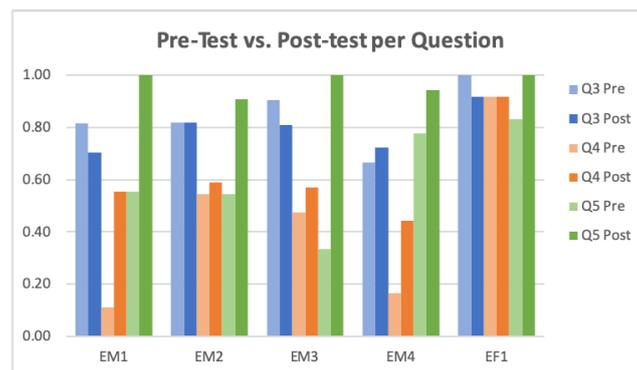


Figure 10. Comparison of average pre-test and average post-test grades for the five studied sections (EM1, EM2, ...), and for individual questions Q3, Q4, and Q5, in a scale 0–100.

4.2. Student *t*-Tests and Significance

To determine if the learning gains presented in Tables 5 and 6 were statistically significant, Student *t*-tests were performed for the complete questionnaire and for each question in the tests. A comparison of paired sample means was performed for the complete five-question questionnaire, and also for the three-question questionnaire that resulted from removing questions Q1 and Q2, which already had zero learning gains (see Table 6). For both questionnaires, the grading scale was re-scaled to 0–100 points.

In Table 7, the two-tail *p*-values corresponding to the comparison between $\langle Post \rangle$ and $\langle Pre \rangle$ values are included. The null hypothesis was:

$$H_0 : \langle Post \rangle = \langle Pre \rangle$$

The pre-test and post-test averages and standard deviations as well as the average absolute and relative learning gains, $\langle G \rangle$ and $\langle G_{rel} \rangle$, are also included in Table 7.

Table 7. The < Post – test > vs. < Pre – test > comparison.

N = 111	Pre		Post		G		t-Test	Average
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	p-Value (Two-Tails)	< G_{rel} >
5-question	77.8	19.2	88.3	14.6	10.5	22.0	0.0000	0.473
3-question	63.1	30.3	80.5	24.4	17.4	36.7	0.0000	0.472

It can be seen from Table 7 that the learning gain between the average post-test and average pre-test is statistically significant for both questionnaires (p -value < 0.05), thus the null hypothesis H_0 is rejected. Comparing the three-questions questionnaire with the five-questions questionnaire, it can be seen that for the three-question questionnaire the average pre-test and post-test values are lower, but the absolute learning gain is larger (17.4 points). The relative learning gains are similar for both questionnaires (0.472), and the p -values are zero up to four significant figures also for both questionnaires.

From Table 6, it can be observed that the learning loss for question Q3, noticed previously, is not statistically significant ($p > 0.05$). This suggests that overall, the use of a visuo-haptic simulator had no impact on improving or worsening students’ understanding of the dependence on the distance of the electric force between point charges.

On the other hand, the learning gains for questions Q4 and Q5 are very good, in particular for the latter. The use of the visuo-haptic simulators had a positive impact on improving the understanding of the distance dependence of electric forces between a point charge and a line distribution (Q4) or a plane charge distribution (Q5). The statistical significance provided by the low p -values ($p < 0.05$) confirms this result. The effect on question Q5 is particularly remarkable: most students obtained the correct answer for the plane charge distribution in the post-test.

4.3. Effect of the Previous Knowledge of the Students

The analysis for questions Q3, Q4, and Q5 was also performed for the four EM sections and the EF section alone (see Table 1). The results are presented in Table 8 and Table 9, respectively.

Table 8. Average learning gains per question for the four Electricity and Magnetism course (EM) sections.

N = 87	Correct Answers Proportion		Gains		t-Test
	Pre	Post	G	G_{rel}	p-Value (Two-Tails)
Q3	0.805	0.770	−0.035	−0.042	0.5516
Q4	0.310	0.552	0.242	0.351	0.0010
Q5	0.540	0.977	0.437	0.950	0.0000

From Table 8, it can be observed that the students from the EM sections showed the same trend discussed above for the entire student sample. They obtained significant learning gains for questions Q4 and Q5, especially in this latter, where almost all students answered it correctly in the post-test. On the other hand, the observed learning loss for Q3 was also not statistically significant.

Table 9. Average learning gains per question for the Electromagnetic Fields (EF) section.

N = 24	Correct Answers Proportion		Gains	
	Pre	Post	G	G_{rel}
Q3	1.000	0.917	−0.083	−0.083(*)
Q4	0.917	0.917	0.000	0.000
Q5	0.833	1.000	0.167	1.000

(*) Calculated with Equation (7).

For the EF section, the hypothesis test was not performed to compare the proportions because the well-known large sample criterion $N * P > 5$ and $N * (1 - P) > 5$ is not met [31], where P is any proportion of correct answers in *Pre* or *Post*. From Table 9, it is interesting to note that for the more advanced students of the EF section, the learning gain increased only for Q5 (plane charge). Note also that all EF students obtained the right answer for question Q5 after using the simulators ($\langle G_{rel} \rangle = 1$).

4.4. Perception Questionnaires

As mentioned before, at the end of the haptic interaction session, all students were asked to fill out an exit perception questionnaire about their experience when working with the visuo-haptic simulators, on a Likert scale, with 1 = Totally disagreement, 2 = Disagreement, 3 = Neutral, 4 = Agreement, and 5 = Total agreement. In Figures 11–13 below, results derived from the perception questionnaire, indicated as percentage of the total number of answers for the whole student sample ($N = 111$), for questions QP1 (Figure 11), QP2 (Figure 12), and QP3 (Figure 13) of Table 4, are presented. The results for each type of simulation (point charge, line charge, and plane charge) are also indicated.

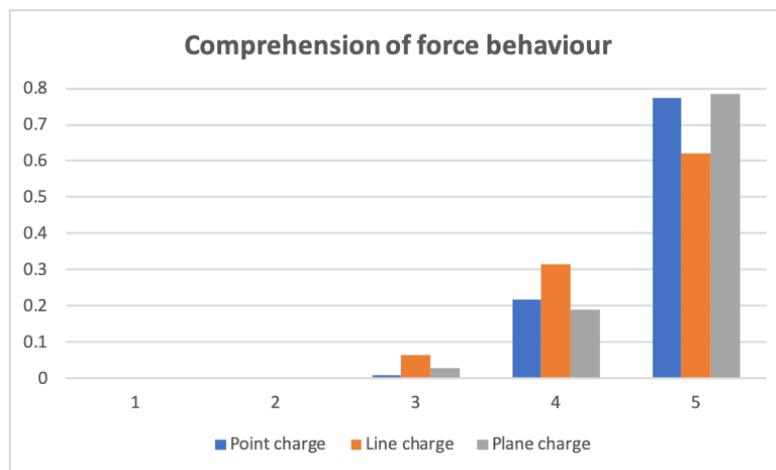


Figure 11. Percentage distribution of student answers given to perception question QP1 “Comprehension of force behavior”, for each of the three visuo-haptic simulators.

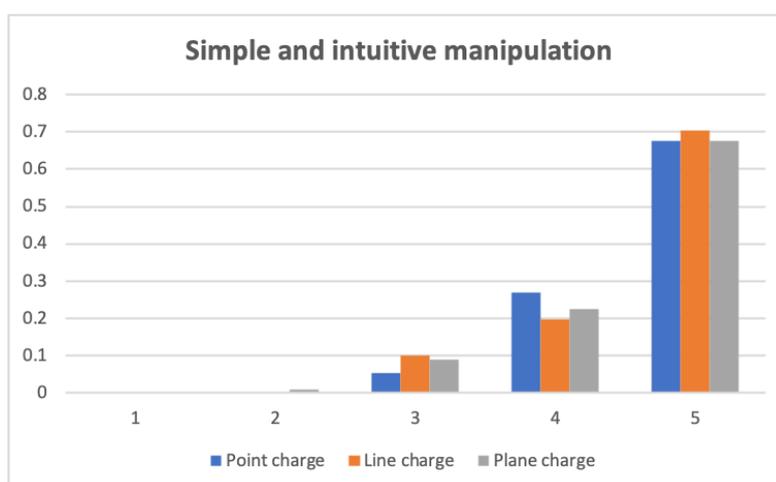


Figure 12. Percentage distribution of student answers given to perception question QP2 “Simple and intuitive manipulation”, for each of the three visuo-haptic simulators.

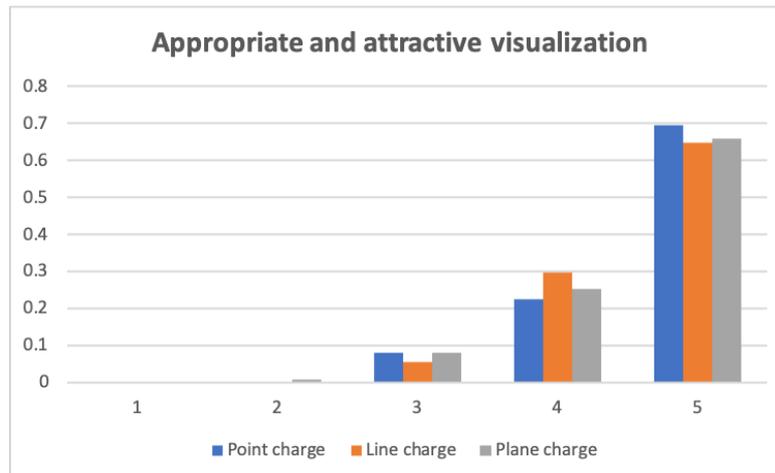


Figure 13. Percentage distribution of student answers given to perception question *QP3* “Appropriate and attractive visualization”, for each of the three visuo-haptic simulators.

As it can be seen from Figure 11, most students consider that the haptic environments helped them to better understand the dependence of the electrical force with distance for different charges distributions (about 95%). Likewise, most of the students consider that the visuo-haptic simulators have a simple and intuitive manipulation (Figure 12) and that the visualization was appropriate and attractive (about 93%, see Figure 13). Derived from our exit survey (see Table 4), Figure 14 shows as percentage of the total sample, the students’ degree of agreement about how much the use of the visuo-haptic simulators helped them to better understand the nature of electrostatic forces, with 97% of “Agreement” and about 75% of “Total agreement”.

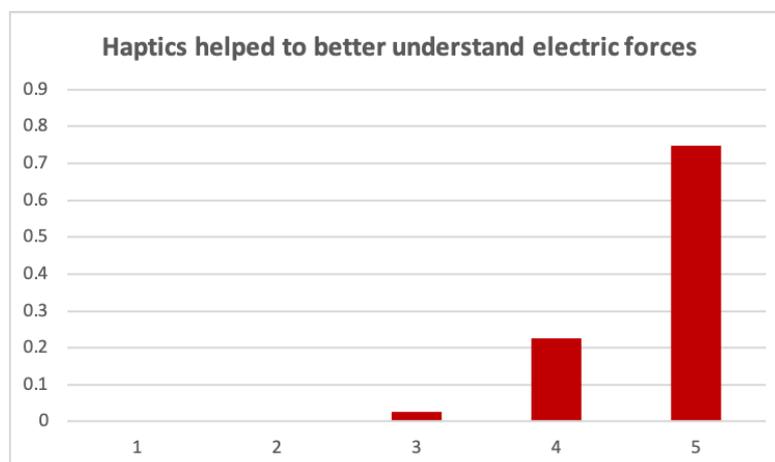


Figure 14. Percentage distribution of the students that consider that the use of the visuo-haptic simulators helped them to better understand the nature of the electrostatic forces, for each of the three visuo-haptic simulators.

Related to this fact, Figure 15 shows as percentage of the total sample, that more than 97% of the students would recommend using haptic simulators to study other themes of Electricity and Magnetism curricula, or other Physics courses.

The last question of the exit survey was an open question in which the students could freely comment on their perception of the haptic devices and their overall experience with the haptic session. The students expressed very optimistic comments and in Table 10 we summarize representative comments.

As it can be seen from Table 10, most of the students liked very much the haptic activity and consider that the haptic devices helped them to better understand the theoretical concepts discussed in class.

Table 10. Excerpt of students comments at the end of the haptic session.

Student	Statement
Student 1	It was a very interesting activity using the devices complements the theoretical knowledge.
Student 2	The activity was really very useful and fun and I think that these types of activities should be used more often in science subjects.
Student 3	I really liked it since we managed to get a better idea of the forces on the charges as well as to feel them.
Student 4	It was very useful to observe the dependency between certain factors and electrical forces. It helped me to complement what was theoretically seen.
Student 5	I liked it and it helped me to understand something that theoretically is sometimes very abstract. It helped me to understand the topics seen in class.
Student 6	It is very educational and fun.
Student 7	Good; however, the instructions could be clearer but the overall experience was excellent.
Student 8	Very good practice, just need to improve the instructions for the activity to deliver.

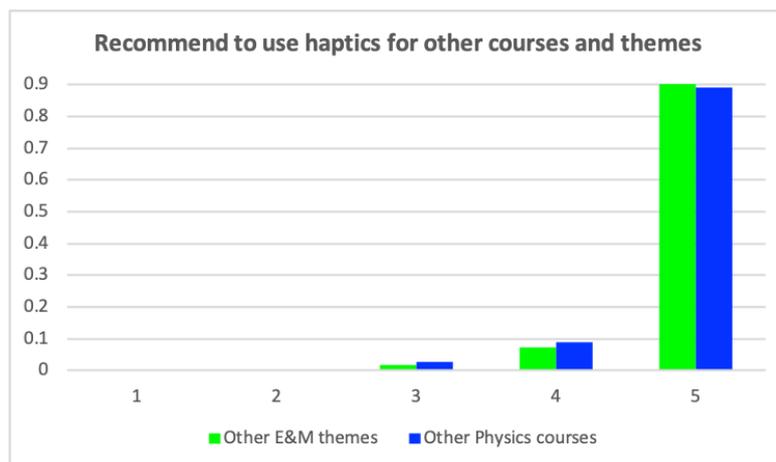


Figure 15. Percentage distribution of the students that recommend to use the visuo-haptic simulators to (a) other Electricity and Magnetism themes (green) or (b) other Physics courses (blue).

5. Discussion

From the results of the previous section (Tables 5 and 6), it can be seen that positive average learning gains were obtained in all student sections, considering the initial five questions of the questionnaire. Given the fact that all students in our sample answered correctly questions Q1 and Q2 of the pre-test and post-test, these questions were removed in the subsequent analysis. This result reflects the fact that all students in the sample already knew the concept that charges of the same sign repel each other, while charges of different signs attract themselves. This basic concept was reviewed at the start of the corresponding courses and was also probably studied in high school physics courses, so the visuo-haptic simulator did not have an impact on it.

From Table 7, it can be noticed that the absolute average learning gains for the three-question questionnaire improved as compared to the original five-question questionnaire for the entire student sample, but average relative learning gains remained similar. Likewise, from Table 6, it can be seen that remarkable average absolute and relative learning gains were obtained for questions Q4 (line charge) and Q5 (plane charge), but a small learning loss was found for Q3 (point charge). The two-tail *t*-tests presented in this table show that the learning loss in Q3 is not statistically significant,

while the learning gains for Q4 and Q5 are. In particular, it is interesting to observe that almost all students in the sample answered correctly question Q5. These results suggest that the experiment involving visuo-haptic simulators helped students to understand the distance dependence of electrical forces for the line charge and for the plane charge, but had a neutral impact on the point charge case. This can be explained by the fact that most engineering students in our sample were already familiar with the $1/r^2$ dependence on distance for the electric force between point charges, because this concept is addressed at the start of all typical electricity courses, so the visuo-haptic simulator is not expected to have a significant impact on it.

The results of this study suggest that the impact on student learning of the visuo-haptic simulators was larger for the EM students than for EF ones. In fact, while EM students obtained statistically significant learning gains for questions Q4 and Q5, EF students only achieved it for Q5. Nevertheless, it has to be noted here that all EF students correctly answered Q5, which suggests that the use of the visuo-haptic simulator helped them to recognize that the force exerted by a plane charge on a point charge does not depend on distance.

The result that EM students obtained larger average learning gains than EF students can be explained by the fact that EF students are more advanced in their careers and their major is precisely related to electronic systems and, therefore, it is expected that they are more familiar with the nature of electric forces. The impact of the visuo-haptic simulators then seems to be stronger on students with lower familiarity with electric interactions. Future work research can be performed with high school or even middle school students to study the degree to which visuo-haptic simulators may have in their understanding of the nature of electrical forces. Additionally, other visuo-haptic simulators, including more advanced topics as electric forces between more complicated charge distributions and/or related with magnetic forces on wires or solenoids, for example, are envisaged for more advanced engineering students.

On the other hand, the perception questionnaires applied to the student sample showed that most students consider that working with the visuo-haptic simulators was an interesting and useful learning experience. They undoubtedly state that the simulators help them to have a better comprehension of the electric force behavior between different charge distributions. Furthermore, they express that the simulators have a simple and intuitive manipulation and that their visualization is both appropriate and attractive, encouraging them to further explore the effect that the input physical parameters had on the corresponding feedback force. Finally, students commented that they would like to have experiments with visuo-haptic simulators in other scenarios related to their courses or even for other subjects.

The learning gains obtained in this research give support to the assumption that the combination of appropriate 3D visualization with an adequate experiment design may promote significant student learning on the nature of electromagnetic interactions. Some previous studies have emphasized the usefulness of visuo-haptic simulators to disclose the nature of electric forces and warned on the need to perform further research to study the possibility of obtaining meaningful learning gains [12,13,27]. Other recent studies had already pointed out that adequate experimental designs were needed. Yuksel et al. [16] and Neri et al. [9] emphasize that the addition of visual cues to visuo-haptic simulators aimed to assess friction forces to increase student perception is a key factor to promote student learning. Shaik et al. [14] suggest the design of adequate guides in the experiments with haptics to improve the conceptual understanding of electrical forces. The authors of [17] have proposed to test different approach sequences of visual cues and haptic feedback to increase student learning of friction concepts. In a recent work, Hamza-Lup and Goldbach [15] explore the advantage of using visuo-haptic simulators to understand the nature of the Lorentz' force and suggest the use of multimodal visuo-haptic games for abstract theory instruction.

Successive research on the use of visuo-haptic studies have increasingly suggested that learning gains can be obtained in Physics learning. While in some works this result was not conclusive [12,13,27], recent approaches with more appropriate experimental designs and instructional guides appear to

point in that direction [8,14–16]. The results of the present research also support the assertion that statistically significant learning gains can be obtained with the use of visuo-haptic simulators when combining an adequate 3D visualization with a carefully designed experimental design through appropriate guidelines for students.

The results found from our exit survey indicate that the students liked very much the haptic activity and that it helped them to better connect the theory with the observations in a funny and practical way. In this sense, the attitude showed by the students toward the use of visuo-haptic systems may be considered as a positively perceived usefulness according to Davis' Technology Acceptance Model [32,33].

An important aspect to consider during the design of experiments using EM visuo-haptic simulators is how students understand the r -dependence of the electric force. This could be due to fact that students actually "feel" the electric force at several distances in the visuo-haptic simulators, or to the fact that they recognized the distance dependencies after fitting functions to the experimental values. It is not clear which thought processes the students actually followed because most answered the post-test before fitting the curves to the experimental data, while others did so afterwards. In this regard, a possibility would be to perform experiments with fixed charge values and ask students to feel the forces at different distances for the different visuo-haptic simulators and compare them. For instance, to determine the charge distribution for which the force decreases or increases faster with distance. This will be a very interesting research line to be performed in the future.

The main limitations of this work are the following. The inclusion of a control group that does not use the visuo-haptic simulators but has equivalent learning materials to work, like lectures or practice exercises, would be desirable. The comparison between learning gains between the experimental and the control group can give an insight into the possible advantages of using the visuo-haptic simulators as compared to traditional learning methods. The number of questions of the pre and post-tests may be increased including both quantitative questions and conceptual qualitative questions. In this regard, the use of recognized gauged concept inventories such as BEMA [34] or CSEM [35] would be very valuable. In particular, questions aimed to prompt students to predict the behavior of the simulator for a given initial physical scenario can be included in the pre-test, post-test, and the student guide, in order to prompt students to corroborate or correct their predictions when working with the visuo-haptic simulators.

It is worth commenting here that curiosity raised in most of the students enrolled in other sections at our institution that were not able to participate in the haptic activity. Some of them wanted to live this experience as well. Since providing students with new learning experiences has always been at the very core of Tecnológico de Monterrey's Mission, haptic devices bring life to abstract concepts that are hard to grasp. More and better scenarios will have therefore to be programmed to take full advantage of haptic technologies.

Other interesting lines of research are mentioned next. The pertinence of separating and comparing the haptic feedback component from the visual display component of the visuo-haptic simulators has to be studied, in order to assess the real impact that the haptic feedback had on student conceptual learning (e.g., [15]). Moreover, the study of the impact on student learning by adding or removing visual cues to the simulators, on one hand, and the implementation of different sequences of instruction interchanging the order of force feedback with the incorporation of visual cues to the graphical user interface, on the other, are other possibilities for future research [8,16,17].

6. Conclusions and Future Work

From the results presented in the previous sections, several conclusions can be obtained. Three visuo-haptic simulators were carefully designed to recognize the dependence on distance of the electric force between different electric charge distributions: point charge, line charge, and plane charge. Engineering students of EM and EF courses practiced with the simulators. Pre-test and post-tests were

applied before and after students used the simulators and average absolute and relative learning gains were calculated. *t*-tests showed that the learning gains were statistically significant.

All students in the entire sample had the correct answers for questions regarding the attractive or repulsive nature of the electric force between charges with different or the same signs. This result is explained by the fact that this is a basic concept first taught in introductory Physics high school courses and also at the beginning of the engineering EM and EF courses, therefore the use of the visuo-haptic simulator did not produce any learning gain.

From the results of this study, it can be concluded that experiment using the visuo-haptic simulator did not help students to better perceive the inverse square dependence of the electric force between point charges. This also can be due to the fact that students already obtained a high average grade in the pre-test; therefore, there was a rather small interval for improvement.

On the other hand, it is inferred that the experiment with the visuo-haptic simulator strongly improved the student recognition of the correct distance dependence law for the line distribution ($1/r$) and the no-dependence on distance for the plane charge distribution. In particular, for the plane charge, the relative gain resulted very high. This finding encourages authors to develop additional simulators for related topics as other electric charge distributions and magnetic forces.

The more advanced students of the EF section already obtained high grades in the pre-test, therefore their average learning gains were not statistically significant except for the case of the plane charge, where remarkably all of them obtained the right answer in the post-test. This result suggests that in general, the impact of the visuo-haptic simulators proposed in this research is higher for students with lower familiarity with electric forces, and therefore they may have an important potential with high school or even middle school students in introducing them to understand the distance dependence of the electric forces for different charge distributions. For the more advanced students, more complex visuo-haptic scenarios may be developed, as probing more sophisticated charge distributions and/or simulators to test magnetic forces on wires and solenoids. This remains as future work.

The learning gains obtained in the present work give support to the hypothesis that the integration of an appropriate 3D visualization with suitable experiment design and a suitable guide of activities may help to promote significant student learning on the behavior of electric forces in the vicinity of a given charge distribution. As additional future work, the authors foresee the design of other simulators for electricity and magnetism forces, as well as for other physics areas. At the same time, authors strongly suggest implementing the use of visuo-haptic simulators since middle or high schools to introduce students to the study of electric and magnetic interactions.

Regarding the improvement of our visuo-haptic simulators, some extensions can be added in the future. The incorporation of electric field lines and equipotential surfaces to the visual interfaces of the visuo-haptic simulators to obtain an enhanced perception and understanding of the electric forces and fields around the charge distributions is highly recommended. Students could move the test charges parallel or perpendicular to the field lines or equipotential surfaces and assess the corresponding changes in the electric force intensity. Moreover, it could be possible to design volumetric charge distributions as spheres, cylinders, and spherical or cylindrical shells to test the electric field at different locations, inside or outside the material, for conductor or dielectric materials. A set of this kind of experiment will provide students with a better overall comprehension of the geometry of the electric field around charge distributions. Likewise, magnetic fields visuo-haptic scenarios may have important contributions to the learning of related concepts, such as induction, Ampere's law or Lorentz force.

Concerning the experimentation methodology, it is important to allow additional time for students to practice and explore with the simulators to exploit their full capabilities with more extended guides. Moreover, the implementation of diverse experiment sequences, adding different amounts of visual aids or cues to the visuo-haptic simulators, is strongly suggested to potentiate the haptic feedback contribution to student understanding of the physical phenomena. An important future line of research

will be to perform experiments aimed to disclose whether the understanding of the appropriate distance dependence comes from actually feeling the force magnitude in the simulator, or after fitting curves to the experimental data. With the present study it is still not possible to ascertain the roles of these two possibilities. These are all opportunities for future research.

Our perception questionnaire applied at the end of the haptic activity indicated that most students enjoyed very much the interaction with the haptic devices. Most students also recognized that the use of the visuo-haptic scenarios helped them to better understand the concepts related to the dependence of the electric force on distance and allowed them to lively perceive abstract concepts discussed in class.

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