





Article

Assisted Discovery Based Learning of the Electric Force with Scaffolding for Novice Students

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Abstract: Despite being one of the pillars of physics and a well-known subject, the electric force is sometimes not immediately evident to students. Discovery-based learning has proven to be very effective in science education; nevertheless, it can become stressful for students if they don't have the necessary scaffolding and training to construct knowledge by themselves. In this work, examples of obstacles to students were the absence of the necessary background knowledge, distractions in multimedia environments, and that some students prefer regular instruction in order not to be left alone in the face of active learning dynamics. Therefore, we designed and implemented an assisted active learning sequence that includes moderated intervention from two different lecturers on an Electricity and Magnetism course at a private university in Mexico to compare the normalized learning changes with a standard directed lecture. The primary objective of the active learning sequence was to introduce students to the discovery of the electric force via a simulated experiment using a web-based physics simulation, Newtondreams. By comparing normalized learning changes between four groups, two control, and two experimental groups, we show that students in the experimental groups performed significantly better than the control groups ($\langle c \rangle = 0.469$ and 0.435 for the experimental groups, and $\langle c \rangle = 0.08$ and 0.077 for the control groups). We performed a Wilcoxon Rank-Sum Test to examine the normalized gains between the groups. Observed p-values show that there is significant difference between experimental and control groups: CG1 vs. EG1 ($p = 0.00109$), CG2 vs. EG2 ($p = 0.00079$). On the contrary there are no observed significance on the effect of the instructor CG1 vs. CG2 ($p = 1$), EG1 vs. EG2 ($p = 1$). Then, that active learning is more effective than regular instruction. Studying the concentration factors we also found that active learning develop better comprehension that regular instruction lecture. At the end of the experiments, we performed student interviews that also showed they felt less stressed and more involved when using the assisted active learning sequence, making the learning experience more amenable when the instructor changes their role from presenter to a guide.

Keywords: instructional scaffolding; active learning; STEM education; discovery based learning; classroom technology; physics



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1. Introduction

In the last years, in the area of physics teaching, the results of various investigations provide evidence and knowledge that promote the use of innovative strategies based on active learning and student-centered, which improve the academic outcomes compared to those obtained from traditional teacher-centered instruction [1–7]. For example, Ref. [1] define active learning as “interactive engagement methods promote conceptual understanding through the interactive engagement of students in heads-on (always) and hands-on

(usually) activities which yield immediate individual feedback to all students through discussion with peers and/or instructors". Besides active learning, the students can be engaged with the course material through problem-solving, case studies, interactive lecture demonstrations, etc.

In an interactive demonstration [8–11], the student challenges their prior understanding of a concept, making a prediction of the outcome of the demonstration. After that, in small groups, they experience the demonstration using a simulation, collecting or working with data, taking a survey, or conducting an experiment with the intention to determine if their initial beliefs were confirmed or not. Finally, the students compare their beliefs with the results of the demonstrations and make a reflection on them. In such demonstrations the use of interactive simulations in the undergraduate physics classroom, becomes even more effective due to student engagement and knowledge ownership [8,12–21]. Such discovery-based learning can be assisted or unassisted. Nevertheless, many authors maintain that it shouldn't be applied totally unassisted [22]. Similarly, discovery-based learning is very effective in science education. Still, it can become stressful for students if they don't have the necessary scaffolding and training to construct knowledge by themselves [23,24]. In this situation where students fall in a cognitive gap that prevents them from finishing the task individually, Vygotsky [25] stated, in his brain-based approach to learning, that there is a zone of proximal development in which, with appropriate assistance or guidance, they could achieve the task. Also, Brunner [26] believed that discovery-based learning could not be made a priori or without at least some knowledge base in the domain in question. More effectively, guided discovery takes the student through the path of experimentation avoiding knowledge gaps that could otherwise interfere in the learning process. Moreover, it is beneficial in developing the initial stages of executive function [27]. However, in practice, interruptions and distractions interfere with interactive learning and affect the learning environment considerably [28–35], making the development of new strategies necessary.

1.1. Background

Since many students did not have prior formal instruction on the topic (e.g., no electricity high school course), the strategy used constructivism based on their basic notions [36–40], they start with their own concepts and interpretative schemes of a broad spectrum of Physics topics. For instance, Ref. [37] said that, "a sense of mechanism is the knowledge that provides us with the capability to: (i) Assess the likelihood of various events based on generalizations about what does and does not happen. (ii) Make predictions and postdiction. That is, one can trace entailments forward or backward in time, explaining what will happen on the basis of what is the case, and explaining what must have been the case in order for the present circumstances to exist. (iii) Give causal descriptions and explanations. That is, one can look at a physical event and assign credit or blame for what happens to certain aspects of the circumstances and to general facts about the world".

In the particular context, we had found that many of our students have not seen before (high school) the electric force concept in the classroom or do not remember it at all. This represented another challenge for the application of active learning. In our prior attempts, students stated that they felt lost and preferred direct instruction from the lecturer because of the lack of prior formal instruction in the topic. Previous to this work, we conducted a pilot survey to half of the students in the physics courses, thus, we randomly selected 61 students to analyze their electric force concept's background. It is worth mentioning that the 61 random students in the pilot survey belonged to a previous generation; hence, they were not part of the sample for the main work. It showed that only 30% remembered Coulomb's Law from their high school courses; the others (57%) commented not remembering any electricity topic. This test also noted that our sample of students' background is heterogeneous; only 45% of the total came from a concentration of engineering; the others from areas such as business, health, programming, and business management (see Appendix A for more details on the survey).

This also reveals a local reality, in Mexico, that almost no student demonstrated high proficiency in science, reaching a proficiency level of 5 or 6 at the Programme for International Student Assessment (PISA) 2018 [41]. About 53% of students reached level 2 or higher in science. At level 2, students can recognize the correct explanation for familiar scientific phenomena and can use such knowledge to identify, in simple cases, whether a conclusion is valid based on the data provided. At level 5 or 6, students can creatively and autonomously apply their knowledge of science in a wide variety of situations, including unfamiliar situations.

In 2010, the educational system in Mexico experienced several changes, including introducing the teaching methodology based on competences; this methodology is still currently in use. While this system intends to promote social and learning skills rather than just transmit knowledge, its implementation has represented a major challenge for instructors [42], resulting in difficulty in developing the promoted skills [43]. In our first attempts to implement interactive learning in the classroom and physics courses, we found many obstacles, such as finding a suitable digital physics simulation that fulfilled the technical and academic requirements for the lesson. Besides, when students access the web, they also faced distractions from the virtual environments and the web itself, so that it is hard for them to remain focused on the task.

Distractions in virtual environments and websites such as instant messaging, streaming music and non-music audio, video streaming, games, mobile and computer-based applications, web surfing, etc., represent an additional challenge for some students, which may be associated with their ability to filter the distractors effectively (see for example [31]). This is why it is important to reduce distractions and interruptions to achieve the greatest possible deep engagement. In the application of virtual activities, it is, for example, very convenient to facilitate and reduce navigation between virtual tools, such as moving between different software or operating systems to run the virtual tools that can make learners face distractions [32]. For such reasons, it was decided to create and release our own web-based experiment repository: *Newtondreams* [44]. These simulations are ready to be used without any additional configuration nor software package installation, which helps to reduce distractions. *Newtondreams* covers three main digital simulator areas: Physics, Statistics, and Mathematics. A short discussion on the repository and the simulation used in this work is made in Section 1.2.

In this work, we designed and applied an assisted active learning method to help students develop knowledge without being overwhelmed due to knowledge gaps or by their lack of acquaintance with active learning. For such purposes, we designed and studied a learning sequence with limited instructor assistance using, as a cognitive tool, the digital simulation *NewtonDreams* [44]. We divided a sample of 140 second-year undergraduate engineering students at a private university in Mexico into control and experimental groups to get two types of lessons, one being a direct instruction class and the other, an assisted active learning sequence. We present our methodology in Section 2. We compare and discuss the effectiveness of both lesson types and present the obtained results in Section 3. Finally, in Section 4 we share our conclusions.

1.2. The Web Based Simulation: *Newtondreams*

Physics simulations have been observed to be highly engaging and educationally effective cognitive tools [45–48]. Their use has promoted a constructivist learning environment [49,50], where creativity is motivated by familiarising and encouraging the student to interact with physics phenomena. There are many initiatives in this direction, such as Open Source Physics [51], Conceptual Learning Of Science [52], and PhET Interactive Simulations [53], the most widely used. All of them attempt to be self-exploratory by students.

However, because we attempt to provide a quickly accessible cognitive tool even with a limited internet connection, the simulation used in this study belongs to the *Newtondreams* project [44], a web-based repository which can be accessed through the web-site www.newtondreams.com.

newtondreams.com (accessed on 1 April 2022). Newtondreams aims to provide simulations for guided virtual experiments with a low computational cost and no restrictions of pre-installed software or technical specifications for available computing equipment. With such intentions, simulations are programmed directly in HTML/Javascript, so they would not require the downloading of extra libraries or packages and would then be operating system independent. The simulations can run on any device such as tablets, smartphones, PCs, laptops, and even smart TVs as long as they have a web browser. Currently, it is only available in Spanish. To run the simulation, students only need to load the simulation once into the browser; then, it can run even without an internet connection.

To help students focus on the main topic, simulations are depicted in a plain environment with a straightforward menu; each one has a main illustration of the physics concept to be studied and a pair of sliders where students can manipulate the main variables. This way students, can observe the relation between the involved parameters (e.g., what happens to the electric force as the magnitude of the charges increases).

In this study, students worked in groups. We requested at least one laptop per group to run the simulation as a team, though sometimes students desired to attend the activity individually on their smartphones or tablets. Complementary, because the lecturer interacts personally with the groups, the continuity of the session is supported, and distractions such as those present on the web are avoided.

The cognitive tool simulation used in this study is named *Fuerza Eléctrica* (Electric Force). It presents two charges that students can move in different positions in the x-y plane by dragging and sliding from each other, to change the electric force magnitude and direction. This allows students to visualize the effect of distance, magnitude, and the sign of the charge in the electric force and look at the superposition concept using 3 or more charges. It presents the exact values of the charges, forces, and their angle from the positive x-axis. Students can deduce or prove the precise relationship between variables and test their predictions. An example can be seen Figure 1.

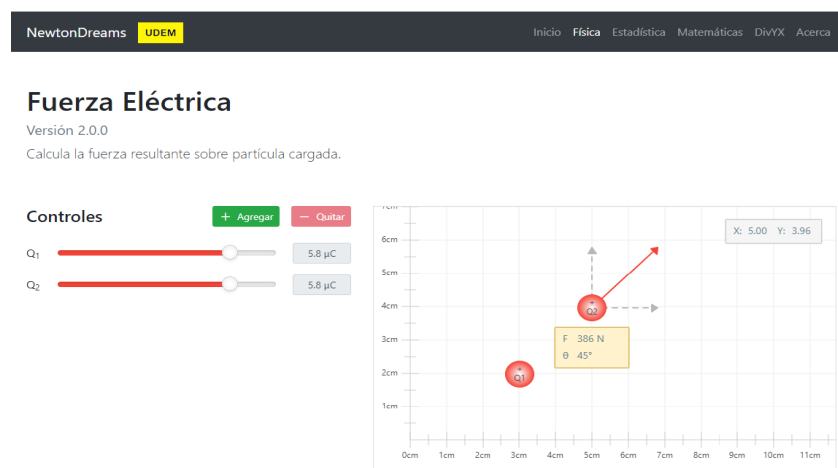


Figure 1. The Newtondream simulation of two charges interacting to illustrate the Electric Force [44].

2. Methodology

This work aims to compare the effectiveness between a direct instruction lecture and an assisted active learning sequence. So that, the research questions (RQ) are:

- RQ1. Is an assisted active learning session more effective than regular instruction for novice students?
- RQ2. Does guided virtual experimentation achieve a better comprehension than a textbook-based strategy?

For this purpose, we divided a sample of 140 second-year undergraduate engineering students enrolled in the Electricity and Magnetism course at a private university in Mexico into control and experimental groups as described in Table 1. Two lecturers with plenty of

teaching experience in the electromagnetism course participated in the experiment; each one led a control and experimental group. Since it is the first-course session, the students take the session without prior preparation in both the experiment and control group.

Table 1. Description of control and experimental groups. Two lecturers participated in the experiment, and each one led a control and an experimental group.

Group Type	Lecturer	Number of Students	Label
Control	1	32	CG1
Control	2	35	CG2
Experimental	1	37	EG1
Experimental	2	36	EG2

2.1. The Control Groups

The control group received a 60 min regular instruction session which was lecturer-centered using the blackboard and a PowerPoint presentation as a visual aid. The content follows the Chapter 23 in [54]. The lecture was organized as follows, lecturers made an introduction of the topic, then explained Coulomb's inverse-square law, then they solved textbook exercises.

2.2. The Experimental Groups

In the experimental groups, the 140 students were randomly assigned into teams of 3 to 4. To each team, the lecturer gave a single active learning sequence on 60 min long, which aimed to guide the student to discover the electric force concept by experimentation using a web-based physics simulation that provides virtual contact with the phenomena. Once students were divided into groups, they were ready to start the activity on their work-spaces, the lecturer presented the Newtondreams simulation and show them its basic functionality. The learning goal is to understand the force's vector nature and the relationship between force, charge, and distance.

In the experimental groups, six tickets were given to the students at the beginning of the session at Part 1. Lecturers explained to students that tickets represented an opportunity to ask the teacher a straightforward question guiding the students with hints, trigger questions, analogies, etc., if they felt they needed, for instance, when they had specific questions, doubts, or if they felt stuck in the learning process. This also kept them from feeling anxious about the exercise. Furthermore, when students used tickets, lecturers were instructed to help them conclude and solve their doubts by themselves.

The active learning sequence consist of 3 main parts,

1. (~15 min) The qualitative exploration; in this part, students are asked to make predictions of the behavior of the forces between electric charges; afterwards, they probe their predictions using the simulations. Finally, they describe the observed behavior with simple statements in their own words. They explore the relationship between force, charge, and distances and the vector nature of electric force. In this part, lecturers specified that it is an exploration activity, and there would be no penalties, especially if their predictions were incorrect. See for instance, the top panel of Figure 2 to see questions examples asked for the students predictions.
2. (~20 min) The quantitative exploration. Students analyzed the numerical relationship between variables through trigger questions in the sequence.
3. (~25 min) The synthesizes. Students identify the equations and models that describe the phenomena, the Coulombs law. In Figure 3, the are asked to build a table of F vs. r and then plot it with the aid of MS excel. Then they fit a curve to the data and find which formula fits better the observed data. They find that the best formula is r^{-2} . Further, in the sequence's next item, they identify the inverse square relationship between F and r .

4) Predicción - ¿Qué crees que suceda con la fuerza entre las cargas, si la distancia entre ellas aumenta? Explica tu razonamiento.

Disminuye ya que la fuerza que ejerce Q1 mientras más se aleja menos influye en el Q2

5) Prueba tu predicción hecha en 4). Mueve Q2 lejos de Q1 y luego acércala. ¿Qué se puede decir de la fuerza eléctrica y su relación con la distancia entre cargas? ¿Qué sucede al estar las cargas más lejos? ¿Qué sucede cuando están más cerca?

Después de probarlo, podemos afirmar que la distancia influye en la magnitud de la fuerza ejercida; esta aumenta si está más cerca a la carga Q1 y al estar más lejos disminuye

Figure 2. Student sample responses in the active sequence. Questions examples were asked for the students' predictions in the qualitative exploration between the charges. (4) Question. What do you think that will happen to the force if the distance between them increases? Explain your reasoning. Students made predictions based on the fundamental notions and answered (Spanish) "The force decreases, since the further away Q1 is, the less they influence Q2". Then, (5) they were asked to probe it with the simulation and answer a qualitative description. (5) Question. Test your prediction made in (4). Move Q2 away and then move it closer What can be said about the electric force and its relationship with the distance between charges? What happens when the charges are further away? What happens when they are closer? . Answer, "After testing it, we could affirm that the distance influences the magnitude of the force exerted; it increases if it is closer and decreases when it is further away".

16) Usando $Q_1=Q_2=2\mu\text{C}$ llená la siguiente tabla de F_{12} en función de r_{12} . Luego grafica la tabla usando MS Excel y ajusta una función a los puntos para ver cuál expresión se ajusta mejor. Anexa la gráfica en un documento Word.

r(cm)	F(N)
1	360 N
2	90 N
3	40 N
4	22.5 N

17) ¿Cuál de las siguientes formulas describe mejor el comportamiento entre la fuerza y la carga?

a) $F=k/r$ b) $F= k \cdot e^{(-r)}$ c) $F=kr$ d) $F=k/r^2$

Figure 3. Student sample responses in the active sequence. Students are guided to recognize the law of the inverse square. Question (16), Set $Q_1 = Q_2 = 2 \mu\text{C}$, fill the following table of F_{12} as a function of r_{12} . Then plot the table using MS Excel and adjust a function to the points and observe which expression fits the points better. Attach the plot to a word document. Question (17), Which of the following formulas best describes the behavior between the force and the charge?

2.3. Assessment Tools

At the beginning and the end of each session, all students answered a 15 min pre-test and post-test, and some students participated afterwards in a 25 min interview, which were

another form of collecting data. Scores were calculated giving, one point per correct answer and zero points otherwise. These tests were based on questions 3–9 of the Conceptual Survey of Electricity and Magnetism (CSEM) [55]. In Section 3, we discuss the results. The relation between CSEM questions and concepts are shown in Table 2.

Table 2. Relation between CSEM questions and concepts.

Item Number in This Work	CSEM Question	Concept
1	3	Force-Charge
2	4	3rd Law
3	5	Force-Distance
4	6	Superposition
5	7	3rd Law
6	8	Superposition
7	9	Superposition

3. Discussion and Results

3.1. Comparing the Effectiveness between Sessions (RQ1)

To quantify and compare the efficiency of two teaching methods, it is common to use the normalized learning gain defined by Hake [56], given by

$$g = \frac{post - pre}{100\% - pre} \quad (1)$$

where *post* and *pre* are the student's post-test and pre-test scores out of 100%. Equation (1) represents the change in the average score over the maximum possible gain, "the fraction of concepts learned by a class that was not known at the beginning of the course" [57]. The normalized gain has been used to evaluate the teaching interventions in physics all the way back to [56]; since then, it has been widely used as a measure in PER and well-explored (see for instance [57,58]). It has also been used in some of the most seminal studies of reformed teaching practices and teaching interventions in physics, see for instance, Ref. [17] on Peer Instruction, and specifically in the case of electricity and magnetism using CSEM, Ref. [59].

Furthermore, because it has been argued that normalized gains can be biased at the extreme values of *pre* scores [60], in this work, to quantify and compare the efficiency of both methods, we use the normalized learning change as defined by Marx and Cummins in [61],

$$c = \begin{cases} \frac{post-pre}{100\%-pre} & , post > pre. \\ \text{drop} & , post = pre = 100 \text{ or } 0. \\ 0 & , post = pre. \\ \frac{post-pre}{pre} & , post < pre. \end{cases} \quad (2)$$

Once again, *post* and *pre* are the student's average post-test and pre-test scores out of 100%. In addition, we have also computed a correlation test between *g*, *c*, and the *pre*-scores. The obtained *p*-values are $p_{g,pre} = 0.0206$ and $p_{c,pre} = 0.3311$, for the normalized gain and change respectively. Since $p_{c,pre}$ it is not significant, then *c* is less sensitive to *pre*-test than *g*. Hence, we decided to compute the normalized change for each group case, as presented in Table 1. Figure 4 shows our results. The closer to one, the better the learning is. Using R software [62], we found that the normalized change medians are 0.18, 0.0, 0.5, and 0.5, for CG1, CG2, EG1, and EG2, respectively, they are indicated as solid lines in the figure. We also include the normalized change quarterlies. Observed average gains of experimental groups were significantly higher than the control groups, being $\langle c \rangle = 0.469$ and $\langle c \rangle = 0.435$ for the lecturer 1 and 2, and $\langle c \rangle = 0.08$ and $\langle c \rangle = 0.077$ for the control groups.

We also performed a Wilcoxon Rank-Sum Test, using R software [62], to examine RQ1 by comparing normalized gains between the groups. Observed *p*-values show that there is significant difference between experimental and control groups: CG1 vs. EG1 ($p = 0.00109$),

CG2 vs. EG2 ($p = 0.00079$). In general experimental groups show higher normalized gains. On the contrary there are no observed significance on the effect of the instructor CG1 vs. CG2 ($p = 1$), EG1 vs. EG2 ($p = 1$). We show the descriptive statistics in Table 3 and the Wilcoxon Rank-Sum test in Table 4. These outcomes allowed to answer RQ1, supporting that active learning is more effective than regular instruction.

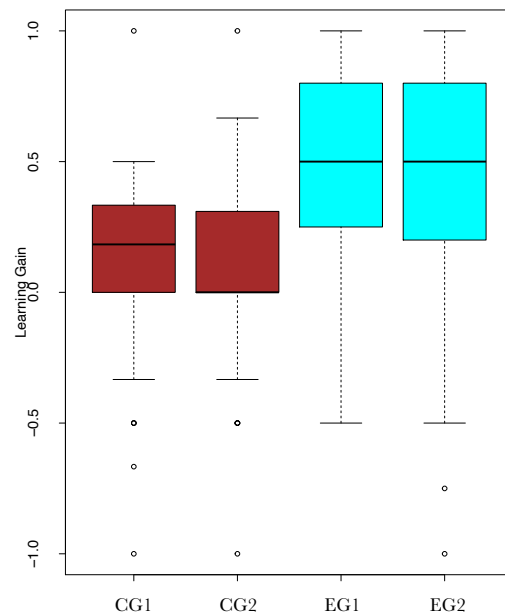


Figure 4. Observed normalized learning change quartiles. From left to right, (brown) the control groups GC1 and GC2, (cyan) the experimental groups GE1 and GE2. The solid lines stands for the medians of each group and dots are outliers.

Table 3. Descriptive statistics on each normalized changes on each group.

Tag	n	Median	Iqr	Mean	Sd
CG1	32	0.183	0.333	0.08	0.409
CG2	35	0	0.31	0.077	0.393
EG1	37	0.5	0.55	0.469	0.357
EG2	36	0.5	0.6	0.435	0.489

Table 4. The Wilcoxon Rank-Sum Test. Where (CG) stands for Control Group, (E) for Experimental Group, and (1, 2) is the Lecturer Id.

Group vs. Group	p-Value	Effsize	Significant
CG1 vs. CG2	0.765	-	No
CG1 vs. EG1	0.000182	0.451 (moderate)	Yes
CG1 vs. EG2	0.000291	0.440 (moderate)	Yes
CG2 vs. EG1	0.0000605	0.473 (moderate)	Yes
CG2 vs. EG2	0.000132	0.454 (moderate)	Yes
EC1 vs. EG2	0.838	-	No

3.2. Comparing the Developed Comprehension (RQ2)

To measuring the comprehension between the regular lecture and the active learning session, we use the concentration factor, that is the students' thinking schemes and how

they change after each learning session. We estimate the concentration factor as defined by Bao and Redish [63],

$$C = \frac{\sqrt{m}}{\sqrt{m} - 1} \times \left(\frac{\sqrt{\sum_{i=1}^m n_i^2}}{N} - \frac{1}{\sqrt{m}} \right). \quad (3)$$

where m stands for the number of different choices on one question, n is the total number of students who selected choice i , and $N = \sum_{i=1}^m n_i$ is the total number of responses. Equation (3) is a measure of the students' answers distributions. It is a normalized variable: if values are larger there are more concentrated answers, with one being a perfectly correlated response and zero a random answer. To have a graphical representation, Bao and Redish propose constructing an "S-C" plot, where S is the test score and C the concentration factor given by Equation (3). S and C can be divided into three different levels, High (H), Medium (M), and Low (L). When combining score and concentration factor, there are six different regions representing the level of concentration. Depending if the responses are concentrated on one choice, two choices or somewhat evenly distributed among three or more choices, these regions are classified into the following categories: one correct model (HH), one dominant incorrect model (LH), two possible incorrect models (LM), two popular models (MM) (correct and incorrect), and near random situation (LL) [63].

To compare the improvements after instruction, we made "S-C" plots for both experiment and control groups in Figures 5 and 6, respectively, and list the change per question in the scores and concentration factors, ΔS and ΔC , in Table 5. We observe that the increases in S and C are larger for the experimental group. The most significant differences are in items 2 and 5, related to Newton's Third Law, in which the control group even has negative values for ΔS and ΔC . We note these changes between S-C factors before and after the lessons with the blue arrows on both figures. The improvements in the S-C factors of the experimental groups is clear. Arrows are larger, and their direction is always towards higher scores and concentration factors. Moreover, contrary to the control group, all points after the lesson in the experimental group are in the MM and HM regions.

The HH (upper-right) is the most desirable region because it is dominated by accurate responses, while LL (lower-left) is the least desirable because a random error dominates it in responses. As we can observe in Figure 5, in most items, the average response in the experiment group migrates from LL towards HH after the active learning session, meaning that responses are no longer random but with definite and accurate reasoning behind them. On the contrary, in the control group (Figure 6), not all items migrate from LL towards HH. Some items even go backward after the session. This means that some concepts remain unclear in a direct instruction lecture, and thus, students still answer randomly. In general terms, comparing Figures 5 and 6, we can observe by the length of the arrows that the increase of accuracy is larger in the experiment group. These outcomes allowed to answer RQ2, supporting that assisted active learning develop better comprehension than regular instruction lecture.

Table 5. Displacements on score and concentration per item.

Item	Concept	Control		Experiment	
		ΔS	ΔC	ΔS	ΔC
1	Force-Charge	+0.15	+0.17	+0.23	+0.15
2	3rd Law	-0.06	-0.06	+0.25	+0.24
3	Force-Distance	+0.12	-0.13	+0.62	+0.19
4	Superposition	+0.21	+0.12	+0.22	+0.22
5	3rd Law	+0.09	+0.02	+0.64	+0.34
6	Superposition	+0.01	+0.08	+0.08	+0.10
7	Superposition	+0.17	+0.06	+0.22	+0.18

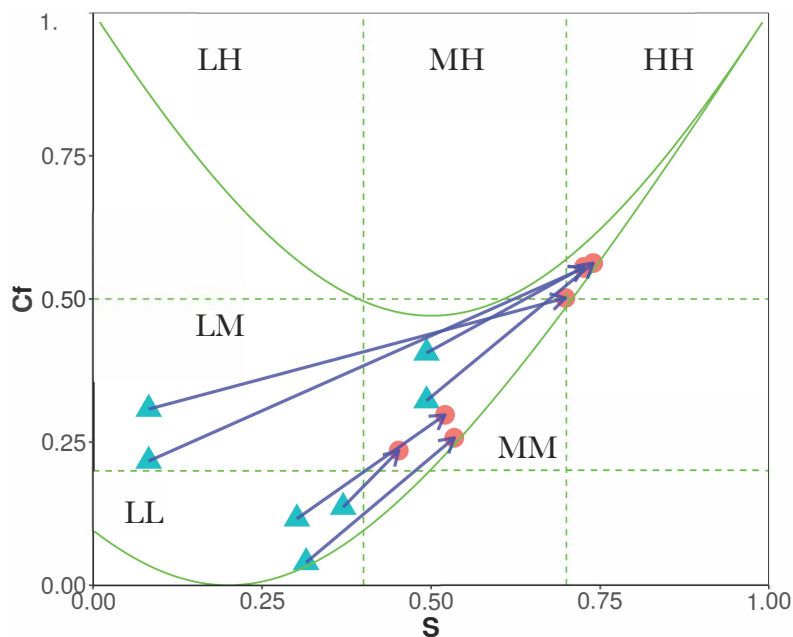


Figure 5. Observed concentration factors (C) and test score (S) before (blue triangles) and after the lecture (red circles) for the experimental group. ΔS and ΔC are represented through the blue arrows per item.

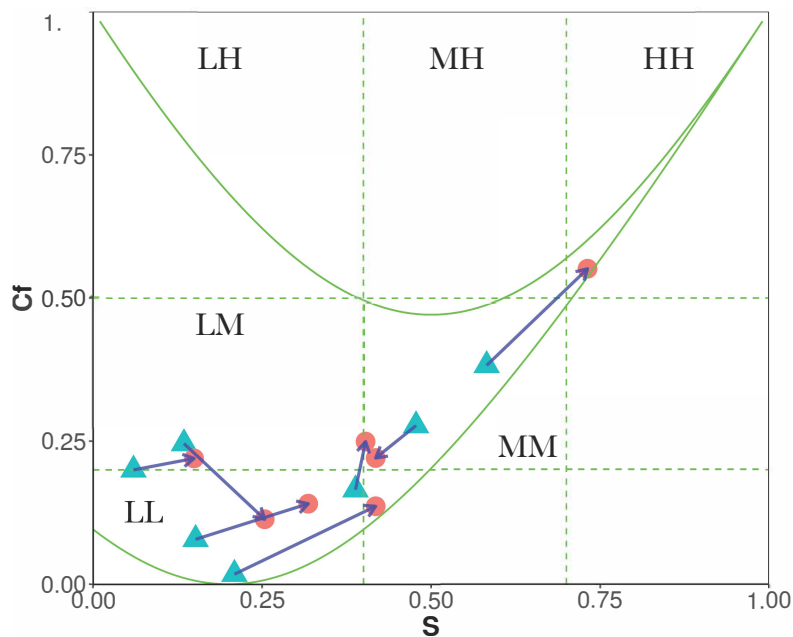


Figure 6. Observed concentration factors (C) and test score (S) before (blue triangles) and after the lecture (red circles) for the control group. ΔS and ΔC are represented through the blue arrows per item.

3.3. Observations on the Question Tickets

When facing doubt or being stuck in the learning process, we want students to argue between themselves before asking the lecturer, so each group received only six question tickets. If they decided to use one of the tickets, the instructor would assist them, giving hints or presenting the situation in different perspectives to help them conclude and solve their doubts by themselves. The questions tickets worked in the intended way. Students worked collaboratively to deduce what they were asked in the sequence because they did not want to spend a ticket. 89% of the teams spent one ticket on the item concerning

Newton's Third Law. Their initial prediction was that when there are two charges of different magnitude, the larger one exerts a greater force on the small one than the other way around. Students were shocked when they saw in the simulation that both forces were equal; some teams even claimed the simulation was wrong. For that reason, they spent one question ticket to clarify their doubts. 44% of teams spent one ticket when trying to deduce the multiplicative effect of charges. A few other tickets were spent in the superposition of forces when one of the charges was negative. It is worth mentioning that many question tickets were spent even when at least one of the students had deduced the correct answer, but the team could not reach an agreement on the answer. It seems that when the student population has very heterogeneous background knowledge, they have trouble reaching agreement. No team spent all of the question tickets.

3.4. Student Interviews

At the end of the experiment, we did interviews with some students to explore their opinion on the activity. This interview lasted 25 min. The objective was to characterize the students' experience of the methodology. We conducted the interviews with 18 students from 73 of the experimental groups, including at least one member of each working group. To obtain open and direct opinions, we held informal group discussions where we asked eight specific questions. This group was selected using a randomized stratified sample, making sure that at least one student per group of the nine original groups was included. An external researcher led the group interviews to avoid any possible bias from the instructors. Here we list some of the representative student answers (between quotation marks) and our comments to five of the eight questions we asked.

- *How did you feel with this teaching-learning method? Did you like it or didn't you like it? Do you prefer to work individually? What do you think?*
 - "It gave us a clearer idea of what electricity really is; I had no idea how the forces were going to behave. This way is better than the teacher explaining everything; you are playing with the app with this method".
 - "I liked it a lot because it takes you step by step on what you have to do and also you could get to the predictions on your own and verify the results".
 - "I liked the simulation a lot because I'm very visual".
- *How about working on teams?*
 - "It's ok to work in teams but in smaller groups, two or three persons, the dynamic works better".
 - "It's ok because someone else from your team can help you if you don't know something".
- *Do you think that it is better to learn this way or do you prefer the traditional method?*
 - "Instead of replacing the classic method, both can be complemented. This helps to generate questions, and then with the teacher, you can understand them better".
 - "This way is easier because you have a question, and you have to look for the answer and find why. It helps you to reason the problem".
- *What advantages or disadvantages do you find in the working method?*

Disadvantages.

 - "Small groups, 3 or 2 persons".
 - "Sometimes you really don't know what to answer because you don't know anything about the subject".

Advantages.

 - "The classic method of teaching for the theory, and the other for visualizing everything better".

- "Both methods complement, then when the teacher explains the subject, we already have an idea and are familiarized with the concepts, and we can understand it better".
- "It gives you previous knowledge about what you are going to see in class".
- "It gives you visual support".
- *Do you feel more or less pressure with this method?*
All students agreed that they felt less pressure.
 - "It gives you a clearer vision about the concepts".
 - "It helps you to interact with the concepts, because of the structure; first you make a prediction, then you can verify it in the program".
 - "It doesn't matter if you were right or wrong, it's a prediction".
 - "This method is more relax".
- *What do you think of the question tickets?*
 - "We didn't have to worry about the number of questions because of the method. We had the possibility to answer our own questions with the app".
 - "They do work because at the beginning with the predictions we wanted to ask everything to the teacher and when we realized that we had a certain number of questions available we said 'Ok, let's try on our own first and save them for later'".
 - "Maybe fewer tickets, because we don't really use it all".
 - "They help to make people work harder".
 - "We didn't use them at all".
- *Was there any exercise that surprised you with its result?*
Students agreed on number 7 (on Newton's Third Law).
 - "We thought that there would be a difference on the force, but they're the same".
 - "We were expecting a difference between the forces".
- *Did you feel you were discovering something about the subject and the concepts when answering the activity?*
 - "Yes, because I didn't know anything about electricity".
 - "Yes, because when we made a prediction, and then we realized that it was ok, it was like -wow-".
 - "Once you discover the relationship between charges, distances and forces, everything begins to fall into place; everything starts to make sense".
- *From the items of the guided experiment, was there any result you didn't expect?*
 - "This one (pointing to the item corresponding to the two charges of different magnitudes, asking which one would have a higher force on the other one). We expected that the big charge would push harder than the small one".

Newton's Third Law seems not to be intuitive for students. In the concentration plots, we also observed that item 5 corresponding to this matter reported significantly higher increases in the experimental group than the control group. Other studies have also stated higher efficiency in illustrating Newton's Third Law by using computer simulation [64].

4. Conclusions

We observe that the normalized learning changes indicate that the implemented assisted-discovery is significantly more effective than the regular instruction, being $\langle c \rangle = 0.469$ and $\langle c \rangle = 0.435$ for the the lecturer 1 and 2, and $\langle c \rangle = 0.08$ and $\langle c \rangle = 0.077$ for the control groups. This method shows to be advantageous when there are gaps in students' background knowledge and when the course's learning objectives are ambitious. If students are operating in their proximal development zone, discovery-based learning with limited intervention from the instructors helps them build their own knowledge and feel empowered.

Interactive learning using web-based simulations reduces stress in students because they feel free to explore and predict without being afraid of the consequences of not knowing the correct answer beforehand. Nevertheless, students also feel that it is appropriate to complement an active learning session with a regular instruction session to consolidate the concepts.

We observed that when the student population has very heterogeneous background knowledge, they have trouble reaching agreement. In this aspect, both the virtual experiment and the limited intervention from the instructors helped them reach a consensus. It would also be a good starting place to explore future directions: this methodology is designed for when the students' background is very heterogeneous, and a good part of the students are afraid to participate and have little experience with active learning. Also, because the lecturer has to provide assistance, this method is limited to small class sizes ($\lesssim 36$). However, this method is particularly appropriate for novice students and does not rely on students with previous backgrounds or preparation. It helps to involve novice students since they feel less stressed for not knowing the concept beforehand. Because of that, we think it may be useful to other educational systems or schools with heterogeneous academic background.

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Abbreviations

The following abbreviations are used in this manuscript:

RQ	Research question
CG	Control group
EG	Experimental group
CSEM	Conceptual Survey of Electricity and Magnetism
S-C	Score-Concentration
L, M, H	Low, medium, and high levels

Appendix A. The Pilot Survey

Lecturers conducted a pilot survey to 61 students to analyze their electric force concept's background. It consisted of two direct questions: (A) What major did you study in high school?, and (B) What topics do you remember from electromagnetism? Results showed that 10% mentioned remembering only Coulomb's Law, 13% circuits, and 20% slightly Coulomb's Law and circuits; the rest (57%) commented not remembering any electricity topic. Furthermore, the quiz shows that the groups are heterogeneous; only 45% of the total came from a concentration of engineering; the others from areas such as business, health, programming, and business management. Thus, the student groups were very heterogeneous. Therefore, because of the heterogeneity of the student groups and the gap in electric force knowledge, we decided to take as a starting point in this work that there was no prior knowledge of such a concept.

Table A1. Pilot survey results. Percentage of students per program.

Answers (A)	Percentage (%)
Engineering	44.3
Architecture and Engineering	1.6
Humanities and Social Sciences	8.2
Business/ Business management/BI course	14.8
Programming	1.6
Health care	11.5
Chemical laboratory technician	1.6
No specialization/Does not apply	16.4

Table A2. Pilot survey results. Percentage of students who claim that they remember the topic.

Answers (B)	Percentage (%)
Coulomb's Law	8
Circuits	13
Coulomb's Law and Circuits	20
Coulomb's Law, but didn't take any electricity course	2
I do not remember (and analogous answers)	57

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