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Investigating the Impact of Visuohaptic Simulations for Conceptual Understanding in Electricity and Magnetism

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Investigating the Impact of Visuohaptic Simulations for Conceptual Understanding in Electricity and Magnetism

Abstract

The present study examined the efficacy of a haptic simulation as a pedagogical tool to teach freshmen engineering students about electromagnetism. A quasi-experimental design was used to compare students who used visual-only simulations to those who used visuohaptic. We hypothesized that multimodal presentation of information may lead to better conceptual understanding of electromagnetism compared to visual presentation alone.

A class of 77 electrical engineering technology students from six different laboratory sessions participated in the study. Laboratory sessions were randomly divided into two groups: a control group with only visual simulations and an experimental group with visual simulations plus haptic feedback. Learning was assessed qualitatively and quantitatively.

Overall results on the pretest and posttest assessments did not demonstrate a significant increase in student achievement of concepts. Differences between the experimental and the control group showed mixed results. Furthermore, results also suggested that students in the control group performed better for specific electromagnetism concepts.

Introduction

With the fast growing evolution of technologies, new forms of complex virtual reality simulations are becoming available and challenging researchers to unravel the components that are effective in supporting learning. An area that has had slow progress in the educational field is the application of haptic technology for educational purposes. Haptic technology involves both touch and kinesthetic motion and affords the user with a sense of touch by applying forces, vibrations, or motions to the hand, providing learners with alternative levels of interaction.

Previous research on the educational value of haptic technology for supporting learning of psychomotor skills suggests that performance of psychomotor skills is better with combined visual and haptic feedback rather than with visual or haptic feedback alone[1]. However, previous studies exploring conceptual understanding have yielded inconclusive results and have yet to provide empirical evidence for the existence of the cognitive impact of haptic technology[2]. We believe that previous studies that have focused on the use of haptic technology for conceptual understanding have not found significant differences because the visual information was sufficient for students to understand simple concepts. This study, in contrast, focuses on more difficult concepts that are not visible to the naked eye. For this reason we argue that understanding concepts that are not visible at the human scale in science and engineering may be better supported when information is presented in visual and haptic modalities.

In this study we investigate the impact of coupling haptic technology in addition to the use of visual simulations for learning electromagnetism in freshmen engineering technology students. Research has proven that abstract concepts such as electromagnetism are not fully understood among high school and college students[3-5]. Likewise, research has shown that students have alternative conceptions about abstract physical concepts that often are not congruent with scientific facts[6-9].

The present study focuses on investigating the impact of visual simulations coupled with haptic technology, specifically targeted to electromagnetism concept learning. The research questions for this study are:

1. What are freshmen electrical engineering technology students' understandings of fundamental electromagnetism concepts?
2. Can students improve their conceptual understanding of electromagnetism concepts after being exposed to visual and visuohaptic simulations?
3. Are visuohaptic simulations more effective as a pedagogical approach than visual simulations for learning electromagnetism concepts?

Theoretical Framework

Dual coding theory guided the design of this pretest-posttest quasi-experimental design[10]. Dual coding theory suggests that learners demonstrate a better concept understanding when information is simultaneously presented in different communication channels. The original study on dual coding theory considered visual and auditory communication channels and their respective working memory. If each modality has its own working memory, it is thought that if multiple channels or modalities are employed the cognitive load on a student can be reduced and more learning can occur[11].

Other researchers have argued that tactile feedback has the same potential role in learning as the visual and auditory channels[12]. Dual coding theory along with cognitive load theory[13], suggest that the use of different working memory channels such as visual and haptic, may allow for more efficient learning.

In the present study, we examine these premises to determine if the use of different (independent or parallel) channels supports better achievement of science concepts.

Understanding and assessing students' cognitive learning, through the exposure of parallel multimodal visual and haptic sensory levels, is the main aim of the present study. As technology rapidly grows, new forms to enhance communication by incorporating sensorial channels through the aid of novel technology are now possible. One of these new technologies is the force-feedback haptic device which provides computer controlled force variations to learners. Aided with this new tactile equipment, and based on the dual coding theory, it is hypothesized that visuohaptic simulations can better support learning, especially with topics that cannot be observed in the human scaled world.

Understanding the impact of these new technologies on students' learning can inform the design of future technologies for virtual environments.

Methods

Research design

This pretest and posttest quasi-experimental design was developed to investigate the impact of visual simulations coupled with haptic technology on electromagnetism concept learning. Groups consisting of 12 to 14 students were randomly assigned to one of the two learning conditions: a control group with only visual simulations (no force feedback) and an experimental group with visuospatial simulations plus force feedback.

Participants

Initial participants in this study included 77 freshmen students from an Electrical Engineering Technology course at a Midwestern University. Eleven participants were excluded from the sample due to incomplete data. Ten of the eleven excluded participants were from the control group (see Table 1).

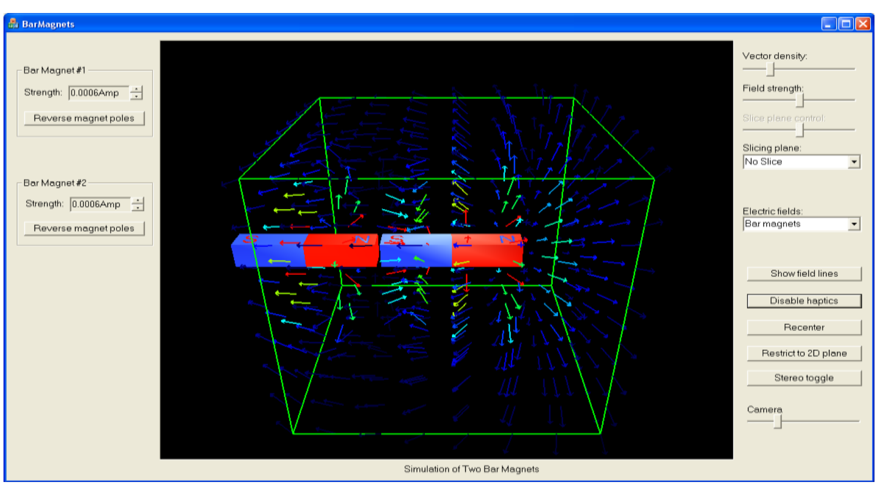
Table 1. Summary of Participants by Learning Condition

	Participants
Experimental	39
Control	27
Total	66

Learning materials

Learning materials consisted of two computer simulations and a haptic device. The subject domain of the first simulation was magnetism. The simulation consisted of two bar magnets with color arrows representing magnetic field vectors enclosing the bar magnets (see Figure 1). The colors indicated the intensity magnetic field (e.g., red- strong, blue- weak). The trajectory of the force is represented by the direction of the arrows.

Figure 1. Magnetism simulation main screen

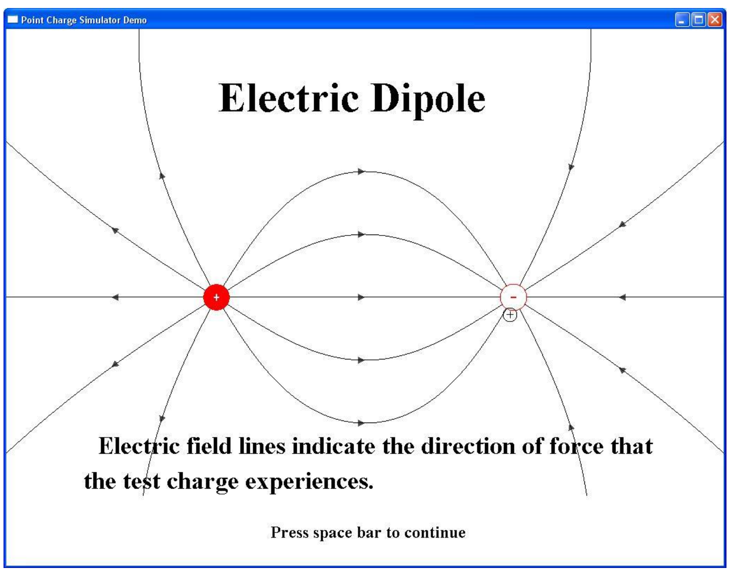


Participants were allowed to modify different characteristics of the bar magnets, such as the strength of their respective poles. Additionally, learners were able to reverse magnetic poles, hide or accentuate vector arrows, and increase or decrease the strength of the magnetic fields. Lastly, the simulation enabled participants to observe different angles of the magnetic field vectors. However, this rotation was limited to a forward and backward rotation.

In addition to the simulation, participants in the experimental condition experienced force feedback (e.g. attraction or repulsion) when approximating the bar magnets' poles, provided by the haptic equipment.

The subject domain of the second simulation consisted of concepts related to electrically charged particles. The simulation started with initial explanations about Coulomb's law and the behavior of charged particles. The simulation then displayed a screen with two static particles as shown in Figure 2. Particles' electric fields were displayed as static field lines indicating the direction of the electrical forces. Participants were able to use the cursor to maneuver a positively charged particle around the simulation screen, except when overlapping the static particles.

Figure 2. Charged particles simulation



Participants in the experimental group were able to feel an attractive force when moving the positive test charge closer to the static negative particle. Similarly, participants felt a repulsion force when moving the positive test charge closer to the positive static particle. Participants in the control group were also able to move the particle around the screen but no forces were delivered by the haptic device.

Both simulations were manipulated using a haptic device called Falcon Novint. The Falcon Novint is a 3D haptic joystick commonly used in video gaming. Participants operated the haptic device by holding the grip and moving it in different positions at will.

Figure 3. Falcon Novint haptic device.

Data collection

Selected questions from Maloney et al.[14] survey of conceptual knowledge of electricity and magnetism were used as the data collection method. The conceptual survey covered eleven topics, from which four were selected for the present study: Coulomb's force law, Electric force and Field superposition, Magnetic force, and Magnetic field caused by a current. The pre- and posttest instruments were identical, and included three questions from each of the selected topics, consisting of a total of twelve items.

Data was collected through an online survey. Aside from these twelve electromagnetism questions, the survey instrument also included three open ended questions that asked participants their name, their assigned laboratory session, and whether they are taking or have previously taken any Physics courses.

Validity and Reliability of the Instrument

The conceptual survey in electricity and magnetism was previously verified and assessed by Maloney et al. Maloney and colleagues validated the survey by asking 42 professors to rate each of the items on a 1-5 scale (1 being low and 5 being high) on reasonableness and appropriateness. Their results indicated that all of the items were rated as highly reasonable and appropriate. The KR 20 reliability score was .75 indicating good reliability.

We conducted an additional expert evaluation. Three researchers with expertise in electricity and magnetism and science education, independently reviewed the instrument. Researchers' agreement on the appropriateness of the topics and questions targeted to freshmen students was used as a validation for the final instrument. In addition, a pilot study was conducted with seven senior physics students. This pilot study allowed us to identify the duration of the study as well as to make minor revisions to the instruments. Students who participated in the pilot study provided the researchers with feedback about the level of difficulty of the procedures, the level of understanding of the explanations and potential revisions to the wording of the questions.

Data Analysis

Analysis started by interpreting responses similar to Maloney et al., to identify students' understandings of electricity and magnetism. Then, data were analyzed using descriptive and inferential statistics. During the descriptive analysis, average scores and standard deviations were calculated for pretest and posttest scores. Participant's responses were coded as (0) incorrect (1) correct, and analyses were performed for: learning condition, complete sample pretest-posttest scores and by questions' topics. The coded data was next analyzed using inferential statistics. Additionally, initial evaluations of the pretest results were examined by learning condition and by questions' topics. A paired t-test model was used to compare the performance of each learning condition and to assess whether there were any significant differences among groups or items' topics.

Procedures

Data collection took place during a one-week period toward the middle of the semester. Pretest and posttest assessments were voluntary; however, students received extra credit in their Electrical Engineering Technology course for the accomplishment of each of the tasks. The amount of extra credit was assigned by the course main instructor, and had no relation with the score of the participants' assessments. Participants had only one opportunity to complete the assessment (e.g. pretest and posttest), and no questions could be left unanswered.

Analyses and Results

This study reports the results and analyses of the pretest and posttest assessments for the control and experimental learning groups. Additionally, several analyses are reported on the performance of each treatment condition based on the questions' topics.

Analysis of responses by concepts' topics and learning conditions

Participants' responses were analyzed by question topic and the scores were evaluated using t-tests. The objective of this analysis was to verify and examine trends in participants' responses, as well as significant differences between conditions. Responses were compared following the evaluation performed by Maloney et al. in the conceptual survey of electricity and magnetism.

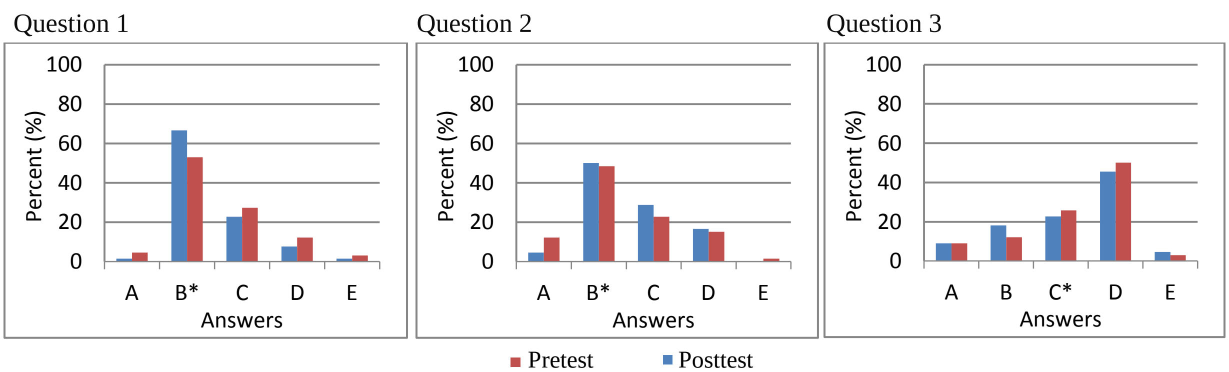
For each of the questions analyzed, responses were graphed and examined based on the pretest and posttest scores of the overall participant sample. Due to the coding procedure of 0 and 1, the highest score a participant could obtain in each of the topics' sections was 3. Responses were normalized to percentages on a 0-100 scale.

<u>Coulomb's force law</u>

Questions 1, 2 and 3 from the pretest and posttest assessments related to Coulomb's force law. Authors classified question 1 as "the easiest item overall" (p. 16). Certainly, results show that the correct answer, choice B, obtained the highest percentage with a 53% of correct answers in the pretest and a 66% in the posttest. An increase in correct responses from pretest to posttest was also noted. Results from question 2, however, showed a reduced number of correct responses. Authors relate this to “favored choice C indicating that many students did not apply Newton’s third law or symmetry of Coulomb’s law to electric point charge situations.” (p. 16). Again, similar to the performance of the experimental group from Maloney et al.’s study, our responses showed answer choice C as the second favored choice. Besides the fewer correct responses obtained in this question compared to the previous item, correct answer option B was conclusively the response with the highest percentage of correct answers.

Lastly, question 3 showed an increase in incorrect responses. Authors relate this issue as “confusion on both the effect of the magnitude of the charge and the distance of separation” (p. 16). Answer choice D predominantly obtained the highest percentages of correct answers with a 50% in the pretest and 45% in the posttest. Contrary of the previous two analyses, question 3 resulted in fewer correct responses on the posttest than on the pretest test.

Table 2. Graphical summary of participants’ responses for pretest and posttest assessments on Coulomb’s force law. Correct answers are marked with an asterisk.



For the Coulomb’s law questions, the mean and standard deviation scores are shown in Table 3. Initial evaluations of the pretests results showed no significant differences between learning conditions. Analysis of the t-test evaluation showed no significant differences between control and experimental group mean gains, (t=.761, p>.05).

Table 3. Results of t-test analysis on pretest and posttest scores on questions 1, 2 and 3

	Condition	Mean	Std. Deviation	Normalized Mean	Normalized Std. Deviation
Pretest	Experimental	1.333	.8057	44.43%	26.86%
	Control	1.185	.7357	39.50%	24.52%
Posttest	Experimental	1.282	.7930	42.73%	26.43%
	Control	1.556	.6980	51.87%	23.26%

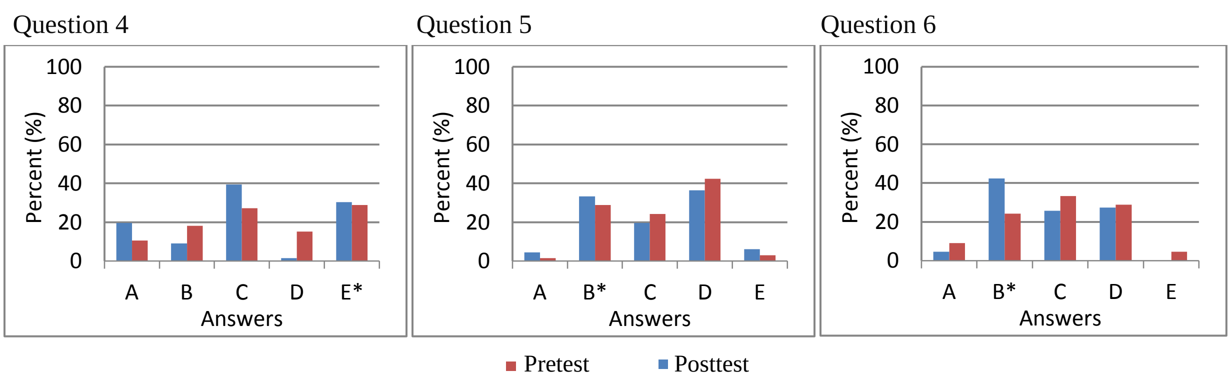
Electric force and field superposition

Questions 4, 5 and 6 from the instrument related to electric force and field superposition. Question 4 indicated a varied combination of choices from participants. Answer choices D and E obtained the highest percentages, although analyses showed that correct answer E was the second favored choice with 28% correct answers in the pretest and 30% in the posttest.

For question 5, the results show a high percentage of answers favoring option D in both pretest and posttest scores. Maloney and colleagues explain this relation as “A noticeable percentage of students seem to be confused about how a new charge affects the direction of the force or field” (p. 16). The second preferred choice with the highest percentages was correct answer B, with 28% of responses correct in the pretest compared to 33% in the posttest.

Lastly, question 6 was the only question from the electric force and field superposition topic that received the highest percent of correct responses, choice B. A noticeable 42% of correct answers on the posttest surpassed the 24% reported on the pretest.

Table 4. Graphical summary of answers for pretest and posttest assessments on Electric force and field superposition. Correct answers are marked with an asterisk.



Electric force and field superposition scores are shown in Table 5. Similar to Coulomb’s law, pretests results were analyzed for both conditions and significant differences were not found. Normalized results show a very similar performance for both learning conditions in the pretest assessment. On the other hand, posttest results show a difference between the two conditions, with the control group (e.g., no force feedback) presenting higher scores. However, t-test results showed no significant differences between conditions (t=-.244, p>.05).

Table 5. Results of t-test analysis on pretest and posttest scores on questions 4, 5 and 6

	Condition	Mean	Std. Deviation	Normalized Mean	Normalized Std. Deviation
Pretest	Experimental	.795	.9228	26.5%	30.76%
	Control	.852	.9488	28.40%	31.63%
Posttest	Experimental	.974	1.0879	32.47%	36.26%
	Control	1.185	1.2101	39.50%	40.34%

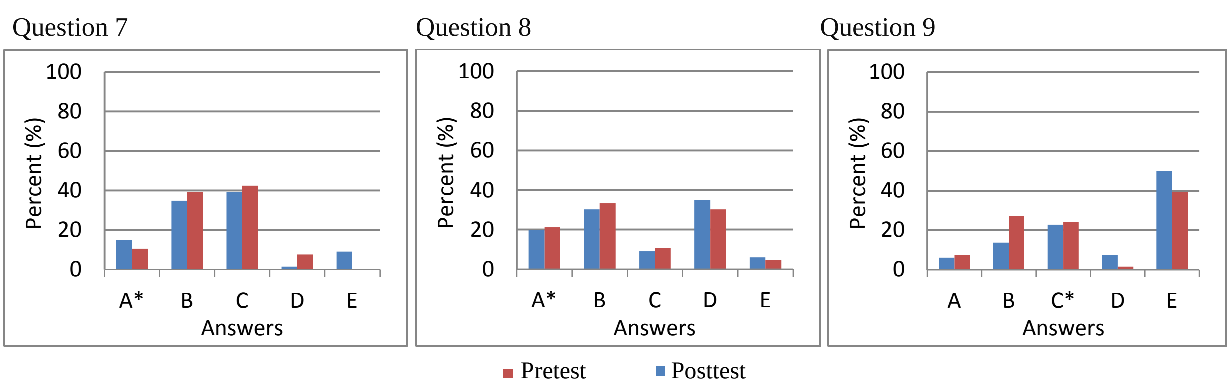
Magnetic field caused by a current

Questions 7, 8 and 9 relate to magnetic fields caused by a current. In question 7, answers B and C were strong distracters for the students. Choice B indicated that students confused the effects of magnetic fields and the effects of electric fields. The percentage of students noting the correct answer A increased from pretest to posttest.

Question 8 tested how much students understood a “magnetic field created by a current carrying wire and superposition of these fields” (p. 16). Although Maloney and colleagues classified this question as straightforward, our results show choices B and D were strong distracters for the students.

For question 9 the strongest distracter is choice E. Authors explained this relation by proposing that it “may be another electrical analog with two like charges and the point in between them having no net field”. Although almost half of the participants chose answer E, the correct answer C got the second highest percentage in the posttest results with a 24% of correct answers in the pretest and 22% in the posttest.

Table 6. Graphical summary of answers for pretest and posttest assessments on Magnetic field caused by a current. Correct answers are marked with an asterisk.



Similar to the previous two t-test evaluations, the data collected from the magnetic field caused by a current topic was analyzed and presented above. Table 7 reports the mean and standard deviation scores obtained from participants’ responses to questions 7, 8 and 9.

First, participants from the experimental condition showed lower achievement than the control group for the pretest assessment. However, pretests results showed no significant differences between groups.

Posttests mean scores show that although control group initially presented higher results, the experimental group obtained a higher mean total.

Table 7. Results of t-test analysis on pretest and posttest scores on questions 7, 8 and 9

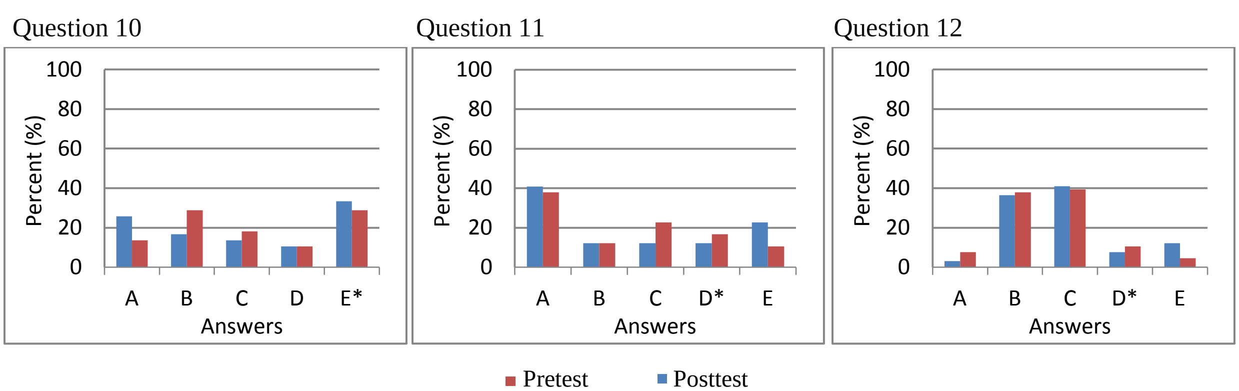
	Condition	Mean	Std. Deviation	Normalized Mean	Normalized Std. Deviation
Pretest	Experimental	.487	.8231	16.23%	27.44%
	Control	.667	1.0000	22.23%	33.33%
Posttest	Experimental	.590	.8801	19.67%	29.34%
	Control	.556	.8006	18.53%	26.69%

Magnetic force

Questions 10, 11 and 12 assessed the topic of magnetic force. According to Maloney et al., in question 10 students often expect a magnetic force when a charged electric particle is placed in a magnetic field. Aside from the high variability presented in the responses obtained from question 10, posttest results show that preferred answer choice E received the highest percentage of responses.

However, for questions 11 and 12, pretest and posttest results show that in both cases the correct answer choice D was noted by only a few students. Maloney and colleagues suggest that this response indicates that students hold an incorrect concept confusing electric force with magnetic force.

Table 8. Graphical summary of answers for pretest and posttest assessments on Magnetic force. Correct answers are marked with an asterisk.



The data obtained from questions 10, 11 and 12 were evaluated and shown in Table 9. Contrary to the previous t-test results, mean scores showed a significant difference between conditions on pretests results, (t=2.64, p<.05). The biggest difference can be seen in that the experimental condition almost doubled the mean score from the control group. This difference was assessed using ANCOVA statistics; however, the condition variable did not impact the posttest results.

Table 9. Results of t-test analysis on pretest and posttest scores on questions 10, 11 and 12

	Condition	Mean	Std. Deviation	Normalized Mean	Normalized Std. Deviation
Pretest	Experimental	.692	.6136	23.07%	20.45%
	Control	.370	.5649	12.33%	18.83%
Posttest	Experimental	.590	.6373	19.67%	21.24%
	Control	.444	.6405	14.80%	21.35%

Difference in pretest-posttest scores

First, sample responses were measured and analyzed based on the overall pretest and posttest scores. Mean scores and standard deviation scores were normalized in a 0-100 scale as shown in Table 10.

Table 10. Means and standard deviations for overall pretest and posttest scores

	N	Mean	Std. Deviation	Normalized Mean	Normalized Std. Deviation
Score Pretest	66	3.212	2.0420	26.77%	17.02%
Score Posttest	66	3.561	2.1635	29.68%	18.03%

The difference between the pretest and the posttest scores was analyzed and measured using *t-test* statistics. A marginal significant difference was found between the two results (t=-1.626, p= .0545).

Similar to the results obtained from the pilot group, these results show that students gained additional knowledge and demonstrated a higher performance after their participation in the learning treatments.

Analysis of responses by learning conditions

Pretests and posttests scores were then analyzed by learning conditions. Initial evaluations were performed on the pretests responses, and no significant differences were found. The difference between scores was considered the gain score. The gain score was calculated by subtracting the posttest score from the pretest score. Gain scores were measured and their mean and standard deviations are reported in Table 11.

Table 11 also shows the normalized mean and standard deviation scores in a 0-100 scale. Participants from the control group (e.g. no force feedback) presented a five times higher mean score than the experimental group. These findings provide evidence that although the control group did not experience the haptic device force feedback, they surpassed the performance of the latter condition.

Table 11. Means and standard deviations for Gain scores by learning conditions

	Treatment Group	N	Mean	Std. Dev	Normalized Mean	Normalized Std. Dev.
Gain scores	Experimental	39	.128	1.9491	1.07%	16.24%
	Control	27	.667	1.3587	5.56%	11.32%

Results were similarly analyzed and measured using t-test statistics. However, the results obtained from the t-test model for comparing Pretest-Posttest gain scores did not show a significant difference between learning conditions (p>.05).

Discussion

Differences among questions' topics

In summary, the control group had higher achievement scores than the experimental group for three of the four topics (Coulomb's law, Electric force and field superposition, and Magnetic Force). This was observed by the higher mean scores presented from pretest to posttest. While the results obtained from the collected data do not provide a consistent pattern on the learning groups' acquired knowledge when analyzing each of the electromagnetism topics, they do present a more positive conclusion for the control group. A potential reason for this outcome is the cognitive overload students from the experimental condition may have experienced[15]. While participants from both conditions utilized the Falcon haptic device, only the experimental group experienced the vibrations and impulses that the equipment provided. The lack of prior knowledge on the device coupled with the innovative sense of forces may have contributed to the over stimulation of students from the experimental group. Additionally, the complexity of simulations and tasks managed by the integration of a new device may have created difficult scenarios for learners from the latter condition.

Findings from overall scores

The difference between the pretest and posttest scores was analyzed and examined throughout the research study. This difference was measured considering the results from the 66 participants as an overall group. The positive increase found in the posttest scores can be supported by the results obtained from the pilot group. Additionally, interesting findings resulted from the t-test analysis performed on the aggregated data where a marginal significant difference between pretest and posttest scores was found. These results can be attributed to the learning process to which participants were exposed. Similar to the results obtained from the pilot group, these results prove that students gained additional knowledge and presented a higher performance after their participation in the learning treatments.

Implications for instruction

Implications in similar instructional scenarios should focus on whether students are cognitively prepared for new educational technology equipment. Instructors should be aware that while providing a different and innovative learning technique, they could contribute to cognitive overload. To reduce cognitive overload, additional experience with the equipment could be provided to reduce the novelty of the haptic technology[16].

Preparation of the instructional materials, as well as more scaffolding through the learning process is also suggested to facilitate the students' understanding[17]. Furthermore, additional research on the use of haptic devices would provide more insight on the possible educational usage of the equipment.

Limitations for the study

The present study had several limitations. In the research implementation, students completed the pretest assessment individually as a take-home task. Although they were instructed not to consult any external material or resource, lack of evidence does not allow us to create any judgment. Likewise, since both assessments were answered voluntarily, participants with incomplete items were disregarded from the overall sample. This later showed an impact on the condition samples size affecting the control group.

A third limitation was the extra credits participants received for completing the assessments. Used as a motivation to participate in the experiment, participants were offered with extra credit after the accomplishment of each task (e.g. pretest and posttest). However, since the extra credit was not related to the score obtained in either the pretest or posttest, students may have failed to provide enough efforts and willingness to obtain a significant grade in the tasks.

Finally, the results of this study should not be generalized until the study can be replicated with a larger sample size. The number of participants in each group was limited. Furthermore, although the students were randomly selected it is not clear whether or not the two groups were equivalent at the beginning of the study. Another possible limitation is the amount of time that is needed for the haptic simulation. Although each group had the same amount of time, it is possible that with additional time the students in the haptic condition would have familiarized more with the force feedback and perhaps would have performed differently.

Conclusion

The data obtained in this study showed mixed results when comparing the performance of an experimental and a control group of freshmen students tested on electricity and magnetism concepts. Unlike the control group who was exposed to only visual simulations, participants from the experimental group were presented with visual simulations coupled with haptic force feedback. During the research treatment, participants utilized two simulations, one related to magnetism and one related to charged particles, and completed different evaluation tools. The pretest and posttest surveys were the only tools covered in the scope of this research article. Results from both condition groups were examined and analyzed by questions' topics, by pretest and posttest scores based on group conditions, and by pretest and posttest results based on the overall participant sample. Pretest results were initially evaluated and no significant differences were found by learning conditions. Similarly, when comparing overall pretest and posttest responses from all participants, no significant difference was found. However, overall results, although not significant, demonstrated a higher performance on the latter evaluation due to treatment exposure.

Results suggest a better performance of the control group in three of the four topics when compared with the experimental group responses. Likewise, pretest and posttest scores resulted in the control group having higher mean scores (but not statistically significantly higher) than the visuohaptic group. It is possible that if the study were repeated with higher sample sizes that a statistically significant difference could be measured. Potential reasons for the results of this study are: (a) participants in the experimental group suffered from cognitive overload, or (b) the complexity of the simulations coupled with a new device created difficult scenarios for students in the experimental group.

Possible suggestions to improve this performance could include previously training participants on the use of new technologies, and by the preparation of the instructional materials to create more scaffolding for participants' cognitive learning.

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