An Initial Study of Visuohaptic Simulation of Point-charge Interactions

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ABSTRACT

We report an initial study on the use of visuohaptic simulation in teaching STEM (Science, Technology, Engineering and Mathematics) topics, with particular emphasis on physics concepts related to the learning of nanotechnology at the undergraduate level. Visuohaptic simulations of point charges and their interactions were developed. Thirty-eight undergraduate students from a physics lab course were recruited to participate in an educational study. Half of the students were assigned to a visuohaptic (VH) group where they could see as well as feel interaction forces rendered with a Falcon force-feedback device. The other half of the students were assigned to a visual (V) group where they could interact with the same simulation via a computer mouse but did not feel any forces. Results from a 10-question content test showed that both groups benefited from the computer simulation. There were no statistical differences between the VH and V groups, presumably due to the relatively small number of participants who completed quantitative assessments. However, qualitative results from observations and interviews indicated that students in the VH groups were more motivated and engaged in the lab activities, reported more positive attitude towards learning, and felt more confident about their understanding and retention of knowledge. Our findings have been used to design a larger-scale study that will further investigate the use of visuohaptic technology in nanotechnology education.

KEYWORDS: Haptics, physics, electric point charge, visuohaptic simulation, nanotechnology education.

INDEX TERMS: H.5.1 [INFORMATION INTERFACES AND PRESENTATION]: Multimedia Information Systems - Artificial, augmented, and virtual realities; H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces (D.2.2, H.1.2, I.3.6 – Haptic I/O; K.3.1 [COMPUTERS AND EDUCATION]: Computer Uses in Education - Computer-assisted instruction (CAI)

1   INTRODUCTION

With the recent advances in nanotechnology, it is important that an engineering undergraduate curriculum includes the fundamental principles needed for an understanding of the interactions among objects at the nanoscale. Most of these physical principles and concepts are too abstract for students to develop an intuitive understanding of traditional instructional materials. For instance, at the nanoscale, the approximation of an analytically continuous charge distribution breaks down and the placement of discrete, quantized electronic charges around nanoscale objects becomes increasingly important. The resulting electric fields and electric forces that exist between electrically charged objects can be calculated, but their distributions become complicated very quickly as the total number of charges increases. These closed-form equations do little to help students develop an intuitive understanding of the force and potential distributions, something that is required in order for the students to develop a sense of the important physics at play, an essential requirement for the creative solving of more complicated problems.

Recognizing the potential of haptics technology in providing a "hands-on" learning experience for students, many researchers have utilized force-feedback devices in teaching dynamics, biology and physics concepts [1-3]. Despite the enthusiastic expectations of the researchers, however, "(previous studies) have yet to provide empirical evidence for the existence of a cognitive impact of haptic technology" [4]. For example, one study allowed students to actively engage in the learning of viruses by controlling an atomic force microscope remotely and through a haptic device [2]. It was expected that the ability to "touch" the viruses might contribute to a more accurate understanding of virus morphology and the three-dimensional (3D) structure of the viruses. It appeared, however, that the use of haptic technology was not a significant factor in student learning, possibly because the visual representations were adequate in conveying 3D spatial information to the students. Another study found the benefits of haptic feedback in a skill training task to be less than clear-cut [5]. Others have found that force feedback can reduce the total force exerted by the user of a surgical robot on surrounding tissues while performing a blunt dissection [6]. It was also demonstrated that, by encoding force information redundantly through both the amplitude and frequency of vibrations on the fingertips, users were able to operate a teleoperation system and judge the weight of objects held by a remote robot [7]. Visual feedback of haptic information has also been found to be generally useful; for example, visual trajectory cue improved performance of unskilled users in a suturing task [8]. In many cases, performance with combined visual and haptic feedback has been shown to be better than that with either visual or haptic feedback alone [9]. The most successful example of haptic-enabled learning and training is perhaps the "Haptic Cow" project [10, 11]. Veterinary students learned bovine rectal palpation on a simulator with force feedback. When compared to a control group who received traditional training, the simulator group did significantly better in terms of uterus identification rates (18/32) than the control group (1/32) [10].

It is our view that haptics will have the greatest impact when presenting information that cannot be easily conveyed visually, such as the haptic identification of internal organs [10], the temporal characteristics of 3D movements [12], or the distribution of interaction forces (magnitude and direction) among objects, as investigated in the present study. We developed an electric point charge simulator using a haptic force-feedback device (Falcon, Novint, Alberquerque, NM). The simulator enabled the students to visualize the force fields and equipotential lines by arranging positive and negative point charges in a plane. Furthermore, the

students could control the position of a +1 unit charge inside the field and experience the forces exerted on the +1 unit charge. To gauge student learning of the topic and assess attitude and motivation, the simulation was used as one of the lab modules in a PHYS 252 Lab course during the Spring of 2009. Next we describe the visuohaptic simulation of point charges and their interaction forces (Sec. 2), and then present the methods and results of the educational study (Sec. 3). Finally, we discuss future work and conclude the article (Sec. 4).

2 POINT CHARGE SIMULATOR

In this section, we present the theoretical physics background of our point charge simulator, and then discuss in detail the visuohaptic rendering of interaction forces between point charges.

2.1 Theory

A charged nanoscale object creates an electric field that influences nearby charges. The electric field has both magnitude and direction, and the magnitude at any point is defined as the force per unit of charge. Therefore, if a charge Q experiences a force F at some point, then the value of the electric field E at that point is given by

$$E = \frac{F}{Q} \tag{1}$$

where the unit of E is in Newton per Coulomb (N/C). The magnitude of the electric field present at a distance r from a charge Q is given by

$$E = k\frac{Q}{r^2} \tag{2}$$

where k is a constant of 8.99×10^9 Nm^2/C^2. Combining Eqns. (1) and (2), the interaction force between two charges Q_1 and Q_2 is expressed as

$$F = k\frac{Q_1 \cdot Q_2}{r^2} \tag{3}$$

where Q_1 and Q_2 denote the amount of charges on the two point charges and r is the distance between the two charges.

A charged object can have a potential energy because of its location in an electric field. The potential energy of a charge Q at any point is defined as the work done on the charge by an external force as that charge moves from infinity to the current position. Potential energy is difficult to measure; it is convenient to discuss electrical potential V instead. The electrical potential is defined as the potential energy per (positive) unit charge. The electric potential due to a point charge Q is therefore given by

$$V = k\frac{Q}{r} \tag{4}$$

where, again, $k = 8.99 \times 10^9$ Nm^2/C^2, Q is the amount of charge and r is the distance. The electric potential is measured in Volts. By definition, V = 0 at r = ∞.

All the points that have the same potential are located on a surface called an *equipotential surface*. In the present study, the charges were constrained to a plane so that it is easier for the students to manipulate the charges. In a 2D plot, the equipotential surface forms a constant potential contour. No work is done by an electric field as a charge moves between any two points on the same equipotential surface.

Given a group of point charges, the resultant electric force on a "test" charge is the vector-sum of the forces from each source charge on the test charge. The electric potential is an algebraic sum of potentials originating from various sources.

2.2 Visuohaptic Rendering

This section describes the visual and haptic rendering of the point-charge simulator.

2.2.1 Apparatus

Two kinds of haptic devices were used for the point charge simulator. In developing the simulator module, an OMEGA-3 device (Force Dimension, Switzerland) was used. The OMEGA-3 is a 3 degree-of-freedom (DOF) force-feedback device with a nominal position resolution of 9 μm. For the educational study where a large number of haptic devices were needed, Falcon devices (Novint, Albuquerque, NM, USA) were used. The Falcon is a lower-cost version of the OMEGA-3, with 3 DOF force feedback and a nominal position resolution of 63.5 μm (derived from 400 dpi). A student could hold the ball interface of the Falcon device and control the position of the ball which is transmitted to a host computer (see Fig. 1). Feedback force is calculated based on the equations presented in Sec. 2.1 and exerted to the student's hand via the ball interface.

Figure 1. A student interacting with the point-charge simulator

2.2.2 Visual Rendering

The point charge simulator was developed with Visual C++, OpenGL and CHAI3D libraries. The software code was modeled after the popular EM Field Version 5.4 software that allows students to visualize electric fields produced by point charges (see http://www.webassign.net/pas/em_field/emf.html). As shown in Fig. 2, a student can click on any positive (filled circles) or negative (open circles) charge displayed at the bottom of the screen and drag it into the main window using a mouse. A click of the left mouse button results in the rendering of an electric field line that passes through the clicked point (Eqn. 2). The arrows along the field lines indicate the directions of the forces exerted on a positive charge. A click of the right mouse button results in the rendering of an equipotential line that passes through the clicked point (see Fig. 3).
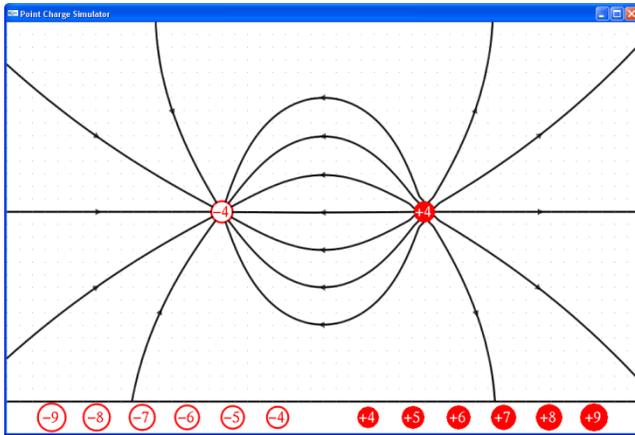
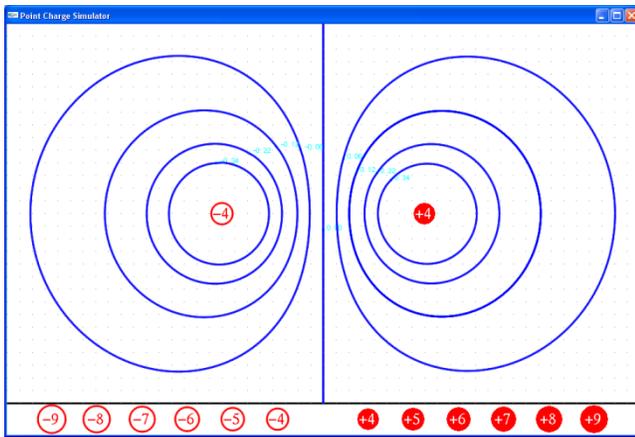Figure 2. Electric field lines in the point-charge simulator

Figure 3. Equipotential lines in the point-charge simulator

Connecting points with the same potential value would have required a global search of the entire display area which can be computationally expensive. Instead, we drew short line segments that were perpendicular to the electric field lines at corresponding points to form a closed loop. This alternative method was fast and took advantage of the fact that electric field lines are always perpendicular to the equipotential lines at points where they intersect. An example of equipotential lines is shown in Fig. 3.

2.2.3 Haptic rendering

To enable the student to experience the interaction forces among charges, haptic rendering was developed to let the student control the position of a positive unit charge (the virtual test charge) in real time. The movement of the haptic device was constrained to a plane by two parallel virtual fixture planes implemented with a PD controller. When the haptic device was activated, the cursor controlled by the haptic interface was displayed as a small circle with a plus sign inside to represent the virtual test charge. The student could drag the test charge into the electric field shown in Figs. 2 and 3 and experience the forces exerted on the test charge as rendered according to Eqn. (3), with the constant k set to $1\text{N}\cdot\text{pixel}^2/\text{C}^2$ to accommodate the force range of the Falcon device. Specifically, the rendered force was the vector sum of the forces between the test charge and each of the charges in the electrical field.

When the test charge approached a positive charge in the electrical field, a repulsive force was rendered through the haptic device such that the two charges could not get too close to each other. When the test charge approached a negative charge, however, an attractive force was rendered and the test charge could be "sucked" into the stationary negative charge. Although the interaction force could theoretically go to infinite when the distance between the two charges is zero (Eqn. 3), the magnitude of the output force was clipped to roughly 1N to protect the haptic device.[1] Unfortunately, the maximum force was large enough to cause the test charge to overshoot the stationary negative charge, resulting in a sudden reversal of the force direction, causing the haptic device to shake unstably. To resolve this problem, an additional repulsive force was added to the electrical force, as shown in Eqn. (5) below:

$$F = K \times (2R - d) \quad \text{when } d < 2R \qquad (5)$$

where R is the radius of the negative charge, d is the center-to-center distance between the negative charge and the virtual test charge controlled by the haptic device, and K is a spring constant. This force felt natural in the sense that it prevented the test charge from penetrating a negative charge, crudely emulating the effect of the repulsive term in the familiar Lennard-Jones potential [13]. Additionally, force feedback was turned off when $d < R/2$.

3 ASSESSMENT

The educational study consisted of two types of assessment: 1) evaluation of students' learning of the basic physics concepts taught during the lab, and 2) assessment of students' attitude and motivation.

3.1 Methods

3.1.1 Participants

Thirty-eight undergraduate students (out of a class of 64 students) participated in this research. All were selected from a one-credit lab course "PHYS252L: Electromagnetism and Optics Laboratory," taught by one of the authors (R.R.) in Spring 2009. Participation was voluntary and informed consent forms approved by the Purdue IRB were signed by all participants. Participants were offered the opportunity to earn extra credit by completing the pre- and post-lab assessments

Of these 38 participants, 28 provided demographic information; Gender: female (3), male (25); Race/ethnicity: White (21), Asian (4), American Indian or Alaska Native (1), Hispanic (1); Age: 18-21 years old (21), 22-29 years old (6); Level: freshmen (2), sophomores (11), juniors (10), seniors (5), other (2).

Student majors included aeronautical and astronomical engineering (1), aerospace engineering (1), atmospheric science (1), chemistry (2), biochemistry (1), computer engineering (2), electrical engineering (2), materials science and engineering (7), mathematics (3), mechanical engineering (1), non-degree (1) and physics (1).

3.1.2 Instrumentation

Content Test: A 10-question, multiple-choice quiz was developed by R.R. to measure student content learning of physics concepts about electrostatic fields and equipotentials. Figure 4 below shows two of the questions as an example.

[1] Our calibration shows that the Falcon is not homogenous in all three axes, and the output force may vary both across the workspace and from device to device.
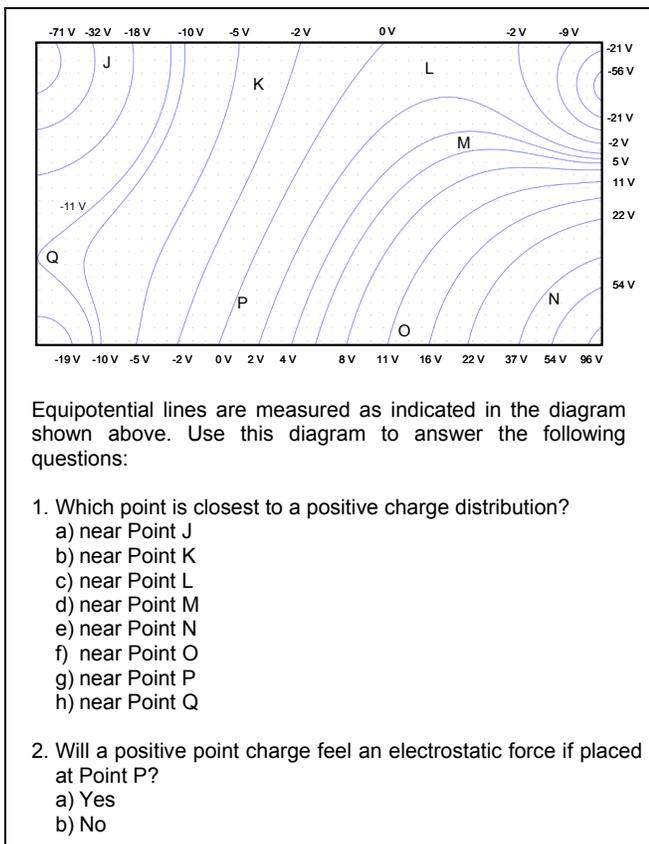
Equipotential lines are measured as indicated in the diagram shown above. Use this diagram to answer the following questions:

1. Which point is closest to a positive charge distribution?
   a) near Point J
   b) near Point K
   c) near Point L
   d) near Point M
   e) near Point N
   f) near Point O
   g) near Point P
   h) near Point Q

2. Will a positive point charge feel an electrostatic force if placed at Point P?
   a) Yes
   b) No

Figure 4. Example questions from the content test.

CLASS: The Colorado Learning Attitudes about Science Survey (CLASS) is a 42 item instrument developed to measure student beliefs about physics and learning physics [14]. CLASS utilizes a five-point Likert scale (strongly disagree to strongly disagree) to measure student perception. Extensive studies of reliability and validity have been reported on the CLASS [14] including factor analysis of scores from over 5000 students. These analyses generated eight empirically derived categories of response: Real World Connections, Personal Interest, Sense Making Effort, Conceptual Connections, Applied Conceptual Understanding, Problem Solving (General), Problem Solving (Confidence), and Problem Solving (Sophistication). Additionally, an overall score summarizes the student's responses to the eight categories.

To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed.
When studying physics, I relate the important information to what I already know rather than just memorizing it the way it is presented.
I enjoy solving physics problems.
I am not satisfied until I understand why something works the way it does.

Figure 5. Example statements from CLASS.

Observations: The students were observed as they worked through the core instructional program.

Interviews: Student dyads were interviewed immediately after the experimental lab sessions about their perception of the lab experience on learning. Interview topics included how students learned best, student perception of the effect of their access modality on the acquisition of lab content and their interest in the lab, as well as a request for general feedback.

3.1.3   Procedures

Students from two lab sessions were assigned to either a visuohaptic (VH) group or a visual (V) group. Due to scheduling constraints, all students scheduled in the same lab session were assigned to the same experimental group. The students in the VH group had access to a Falcon force-feedback device and a laptop running the point-charge simulation software. The students in the V group used the same software with a mouse but did not have access to force feedback provided by the Falcon. The core instructional program, therefore, was identical for the two groups. The main difference between the two groups was the availability of haptic feedback. Students worked in self-selected dyads to complete the instructional program during one two-hour lab period.

Prior to the experimental lab, students completed the content test (pre-test), and the CLASS.

During the lab session, participants were asked to examine electric field lines and equipotential contours for four different charge configurations: (1) a point charge, (2) a dipole, (3) a three charge system, and (4) a parallel plate capacitor. The details of the configurations are as follows:

(1) A Point Charge: Students mapped electric field lines and equipotential contours generated by a point charge and derived the relation between the potential and the distance from the charge;

(2) A Dipole: Students examined the electric field lines and potential contours for a dipole which consists of two point charges of equal and opposite signs;

(3) Three Charges: Students added a third charge to a dipole configuration and examined the changes in the electric field lines and equipotential contours in shape and complexity;

(4) A Parallel Plate Capacitor: Students examined the electric fields and potentials for a parallel plate capacitor formed by two rows of charges with equal and opposite signs separated by a fixed distance.

Students were observed during the lab session. Focus was placed on what each student said, as well as how they interacted with the computer interfaces (Falcon haptic device or mouse).

Interviews were conducted immediately post-lab. After the lab session and post-assignments were completed, students took the same content test again (post-test). At the end of the semester, the CLASS was re-administered, with the delay in administration included to allow for change over time.

3.1.4   Data analysis

A two-by-two analyses of variance with one fixed and one repeated factor were performed on content quiz scores and CLASS category scores. As is typical of the way CLASS data are normalized, CLASS questions were converted from a five level Likert scale to a three point scale (strongly agree or agree = 1; neutral = 0; disagree or strongly disagree = -1).

In order to obtain a more complete understanding to the impact of the experimental condition on student perceptions of learning, quantitative analyses were supplemented with qualitative data in the form of themes from lab observations and student interviews.

3.2   Results

3.2.1   Content test (n=22)

The mean scores on the pre-tests were 51% and 44% for the VH and V groups, respectively. The average scores on the post-tests were 61% and 59% for the VH and V groups, respectively. There was a significant difference (F=5.748, p=.026) between pre- and post-test scores across treatment groups with post-test scores higher than pre-test scores. There were no significant differences between the VH group and the V group from pre-test to post-test (F=.253, p= .621). These analyses indicate that both VH and V groups increased their knowledge of the content covered during the labs, but there was no significant additional learning due to the availability of force information experienced by the VH group. The small size of the groups limited the power of the analyses making it difficult to obtain significant effects for this analysis.

3.2.2   CLASS (n=12)

CLASS results were obtained from four students in the V group and and eight students in the VH condition. There were no significant pre-post differences in CLASS scores for the two groups. Again, the small number of respondents made it difficult to obtain significant effects for this analysis. The simplicity of the experimental tasks may have also restricted the ability to show a benefit of using the haptic channel.

3.2.3   Lab observations (n=38)

During the labs, students were focused and intent on the lab tasks. There were several themes observed with the VH group that were not seen in the V group. First, statements were made that suggested the students were making a connection with previous knowledge, including "the way they explained this in class I wouldn't have thought there would be a difference," and "I thought I knew dipoles, but this is new to me." Second, the majority of student dyads in the VH group took turns interacting with the technology during each task, in contrast to the V group where for the majority of student dyads, one student operated the mouse during the entire lab. Third, positive affective phrases were observed more often with the VH group, both with regard to the technology and the lab content. Examples of affective comments include "we're having way too much fun with this lab," "really cool," and "that is just fun!" Fourth, words related to the sense of touch or the feel of the technology were more prevalent in the VH group, such as "I felt a buzz," "yeah, I can feel the negative force," "out here it is easier to wiggle," and "that was weird because I couldn't pull it away from the positive charge." Finally, with the VH group, multiple students were observed trying things with the haptic technology outside of the assigned lab, saying things like "I wonder what will happen when I do this." No students were observed exploring the technology in the control group.

3.2.4   Interviews (n=38)

During the post-lab interviews, participants were asked how they learned best (see chart below). The 44% of students who identified visual as their best modality made comments that included "learn best by reading," "best to visualize it," "learn visually from pictures," "seeing material," and "power point notes gets me a little more involved in it." Thirty-one percent (31%) of students identified hands-on as their best modality; e.g. "hands-on, doing it," "labs best to learn it practically," and "I study best when moving around." The 17% of students who preferred auditory learning stated that "the teacher talking helps me learn," "learn better by listening," and "hearing key parts helps me recall more." Six percent (6%) of students reported writing activities are their best learning modality, including "copying notes down,""taking notes," and "learn best by writing out a problem over and over

again." The remaining 2% of students reported that they learned best by "talking" or "saying what I need to learn out loud."

Table 2. Results of interviews on how students best learn

% of students	Preferred modality	Included activities
44%	Visual	reading, visualizing, pictures, power point
31%	Hands-on	lab, tactile, kinesthetic
17%	Auditory	lecture, listening
6%	Writing	Repetition, rote-copying
2%	Speaking	Verbalizing content

The majority of students in the VH group reported that the lab was fun. For example., "I enjoyed this lab better than I would have without the fun devices;" "I was more willing to learn the 'lab' because you get to feel it, because it's fun," and "the lab was more fun and interesting than just playing with a computer."

Although approximately one third (1/3) of the students reported that they had previously learned the lab content, many reported that the visualizations and force field feedback in the experimental lab reinforced previous knowledge they had. For example, "when I'm thinking through the electric field lines and electric potential I usually can't visualize it very well, so the lab helped with that," "visuals and feeling it helped because I could see more of what the field would actually do," "it was completely different to feel it than just look at it," and "I learned more by interacting with it (haptic device)."

A common theme among the students in the VH group was that they felt hands-on learning increased their long-term retention of the content. For example, "if you can feel what is going on that will translate into us remembering it longer term," "helped me remember better than if I was just reading the material," "it put an exclamation point at the end that helped drill it in more," and "I'll remember it a little better, makes it much less boring."

4   DISCUSSIONS

We have described an initial study on the use of visuohaptic simulation for teaching physics concepts. This is part of an ongoing project on "Enhanced Undergraduate Nanotechnology Education with Haptic and Visualization Tools." A point charge simulation was selected as the starting point because the real-time visual and haptic rendering provided information that was otherwise unavailable to the students in a traditional textbook. The student participants in the present study were able to manipulate charge configuration in real time, see the changes in electric field and feel the changes in interaction force. It was expected that this would provide a more engaging learning experience for the students involved and lead to a better learning outcome.

The educational study conducted in the present study was a critical component of our investigations. It was important to find out how students would react to the use of the Falcon device as well as to assess, quantitatively and qualitatively, the learning that was achieved. This initial study has provided the project team a valuable experience in planning the logistics of running a larger scale educational study as well as the type of additional data to be collected.

The results from the content tests on physics concepts suggested that both the VH and V groups benefited from the lab activities in that the post-test scores for both groups were significantly higher than the respective pre-test scores. We were however unable to ascertain any additional learning due to the availability of force information experienced by the VH group, partly due to a relatively small sample size used in the present

study. In addition to increasing sample size, it would also be helpful to have a third control group where the students are not provided real-time visual or haptic simulation. This will allow us to ascertain the learning benefits due to visual or haptic simulation separately.

The results of qualitative observations and learning modality questionnaire clearly indicated many positive gains from engaging with the haptic device and visual simulation. Overall, the students in the VH group made more statements expressing connections between the lab activities and prior learning experiences, their use of positive affective phrases increased, they used more touch and tactile words, and only students in the VH group were observed taking turns using the technology.

Currently, we are conducting a large-scale educational study with 180 students randomly assigned to three groups: visuohaptic, visual only, and control group. Three two-hour laboratories have been developed: 1) point charge; 2) dipole and van der Waal forces; and 3) self assembly. In addition to the instruments used in the initial study reported here, additional tests will be administered to a randomly-selected subgroup of students to gauge their innate tendency as a haptic or visual learner.

In spite of not having clear results that the use of haptics and visualization can improve learning of STEM topics, we continue to see anecdotal evidence. The large-scale educational study with stricter experimental design and controls should provide us with stronger indicators relative to the effectiveness of teaching and learning using haptics and visualization.

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