

Computer Haptic Effects in Math and Science Lessons Support Student Learning

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ABSTRACT

This article describes the use of haptic technology to support student learning for middle school students who are blind or visually impaired. Haptic technology allows the students to interact with 3D objects and experience abstract ideas, such as weight or force. These effects were used to help students grasp concepts in mathematics and science. A low-cost haptic game controller was employed to deliver the many different effects that have been created to support the concepts within the computer applications. The goal of our project was to develop computer applications (apps) that would provide access to items that are presented in a visual way or provide experience with an abstract concept. The materials developed are a set of 20 apps created to run on a PC platform and deliver a variety of math and science topics. Each of the apps covers one or two main concepts taken from the newly adopted US math and science state standards. This article focuses on the effects that are used and how they are employed in different apps. The outcome of the testing of these apps in informal and formal settings was positive, showing significant gains from pre- to post-test on the apps.

1. INTRODUCTION

When studying topics in mathematics or science, such as volume in geometry or the layout of the cell in biology, items under investigation are often presented in a diagram or a picture. In many cases these diagrams or pictures are of a 3D representation. In spatial thinking students transform this type of information into knowledge that they use to solve problems. [1] Spatial thinking is accessible to everyone, and spatial thinking skills are necessary for many areas of mathematics and science. Students who are blind or visually impaired often do not have access to the information presented in these 3D visual representations. Current techniques for providing

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access to visual information to students who are visually impaired rely mainly on description, tactile graphics and Braille - utilizing both haptic and auditory sensory modalities. While these methods prove effective for learning from text-based materials and simple graphics, they are not always sufficient for effectively conveying complex 3D information. Some 3D information, such as the parts of a plant cell, is presented to students through the use of molded plastic models. These are effective tools; however, they are costly and possibly only available for a limited number of topics for each student.

Computer haptics can provide a way to allow students who are blind or visually impaired access to certain types of spatial information. Haptic technology has been in use for many years and is implemented in many ways from vibro-tactile sensations on a cell phone to high-fidelity simulations that allow doctors to practice surgery. For this project haptic technology is employed using a haptic game controller that can provide high-fidelity 3D feedback to the user. The feedback helps the student determine such things as the shape of an object, the size of an object relative to other objects, the position of an object in a scene, the weight of an object, the texture of an object, etc. This information can be used in educational materials in the place of diagrams that represent 3D objects, simulations, or even description of more abstract ideas.

This paper discusses how haptics has been used for educational purposes and with students with visual impairments; what specific haptic technology is being used in our project and what effects it can produce; how the computer apps were developed; and the results of testing in both informal and formal learning setting.

2. HAPTICS USED IN EDUCATION

Computer haptics has been used and experimented with for many years. Minogue and Jones [2] give a comprehensive examination of the existing research in haptics and its potential impact on education. These

authors point out that there have been hundreds of articles written on the application of haptic technology in the medical field since 2000. There have also been many studies pointing to the effectiveness of using haptics to increase learning outcomes. In one such study, Project GROPE [3], the researchers found that adding forces (simulated by haptic feedback) to the visual display enhanced users' understanding of the binding energy of a drug molecule. More recently, Jones, et al [4] investigated the effects of integrating haptics into a school biology lesson on viruses. The students were able to interact with the viruses on a microscope slide through the sense of touch. Similarly, the NASA Langley Project developed and piloted software to help students learn about simple machines. [5] This project used a low cost force feedback joystick and included five interactive activities to reinforce concepts presented in the standard simple machines curriculum. Some of the labs included force feedback while others did not. The greatest educational gains were noted for the labs that included the force feedback.

Sjostrom [6] formulated preliminary recommendations for incorporating haptic technology in computer interfaces specifically for users who are blind or visually impaired. The guidelines have been demonstrated to improve performance related to navigation, finding objects, understanding objects, and physical interactions. Some of Sjostrom's recommendations include: (1) providing well-defined and easy-to-find reference points, (2) avoiding changing reference systems unnecessarily, (3) compensating for one-touch-point haptics devices by enlarging interaction points or using magnetic objects, and (4) providing paths to trace in order to find the objects in the scene. Many projects have been able to employ these recommendations when developing haptic-based apps for persons with visual impairments.

Brewster [7] showed that users who are blind or visually impaired were able to accomplish graphical data visualization tasks when the data is presented through haptic and audio channels. The use of non-speech sound and force feedback from the PHANTOM Desktop haptics device significantly improved the interaction of blind students with graphs and tables. Additionally, the use of the Logitech Wingman Force Feedback Mouse and web audio features allowed users who are blind and visually impaired to successfully extract web-based graphical information. [8] More recently McGookin and Brewster [9] have developed and evaluated an application that allows users who are visually impaired to interactively construct bar graphs using a similar haptic device called the PHANTOM Omni haptic device. Although initial evaluation with testers showed that the graph builder was superior to other accepted graph construction techniques used by this audience (corkboard techniques), the authors point out that classroom testing is still needed.

Haptics have also allowed students to interact with "invisible phenomena" in the physical sciences. Clarke and Jorde [10] studied the impact of integrating computer generated tactile feedback into an inquiry project for 120

eighth graders. In this study, tactile feedback was associated with middle school students' improved understanding of thermal equilibrium.

Past projects by the authors have shown that haptics technology can be usable and feasible in an educational setting and show promise for learning. [11] The Advancing Content Through Interactive Virtual Environments (ACTIVE) project was funded by the US National Science Foundation (NSF) Research in Disabilities Education Program. The aim of the ACTIVE Project was to create an interactive learning environment that allowed exploration of the solar system through several senses including touch, sound, and sight. The materials developed incorporated NASA Earth and Space Science data into a virtual reality system including haptics and using the SensAble Omni Device. Evidence showed that the materials created through the NSF ACTIVE project worked as well for students who were visually impaired as for their sighted peers. [11] The pre-test/post-test comparison for the visually impaired group (N = 20) and pre-test/post-test comparison for the sighted group (N = 13) both showed significant learning gains. The comparison between the groups was not significant. The groups both performed equally as well on the assessment. The goals of the ACTIVE Project were accomplished and the resultant prototype instructional system was effective in classroom settings. From this funding, three full haptic systems were purchased and put on loan by the NASA Educator Resource Center.

For this current project, the haptic-based computer apps developed contain high contrast graphics, human-voice audio instructions, and haptic effects so that students can interact with objects in each scene. These apps also incorporate the recommendations suggested by Sjostrom [6] and many recommendations suggested by a team of expert reviewers. These 20 apps cover a variety of math and science topics including: geometry, statistics, algebra, biology, earth science, space science, and physical science. Each app contains between eight and ten scenes and provides the students with many ways for self-assessment. The following sections explain what haptic technology provides and how the apps were developed.

3. HAPTIC TECHNOLOGY

Haptic technology was used in the apps to provide 3D tactile and kinesthetic feedback for students. This section describes the haptic device used for the project and the effects that the device can simulate. Later sections describe the effects and how they were used in computer applications to produce meaningful feedback for students with visual impairments.

3.1 The Falcon® Game Controller

The haptic device chosen for this project was the Novint Falcon Game Controller (Figure 1). The Falcon is a rugged, low-cost haptic controller that provides high-

fidelity three-dimensional force feedback. The controller moves right, left, forwards, and backwards (like a mouse), but it also moves up and down. When a user holds the Falcon's detachable grip and moves a cursor to interact with a virtual object, environment, or character, motors in the device turn on and are updated approximately 1000 times a second, letting them feel haptic effects such as texture, shape, weight, dimension, and dynamics.

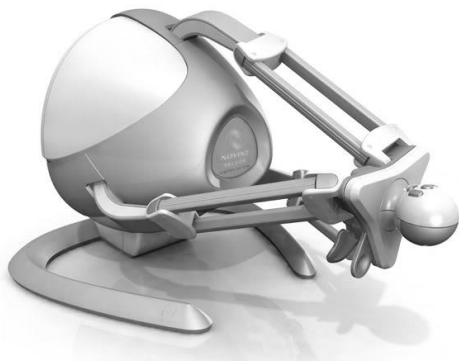


Figure 1. Novint Falcon haptic controller that provides tactile and force-feedback in the apps.

The Falcon provides control and interaction with a virtual environment in a realistic way. It is roughly nine inches by nine inches by nine inches and weighs six pounds¹. The unit consists of three arms attached to a spherical handle or grip containing four buttons. The user manipulates the device by grasping the sphere. The button presses can be captured and used for various functions in the haptic environment. More than two pounds of force can be applied by the controller in any direction.

The Falcon was chosen for this research and development effort because of its low cost (around \$250) and the fact that it is a robust gaming device that has been on the market for over eight years. This device is about one tenth the price of the next cheapest device. The researcher utilized other devices in previous projects (Darrah, 2012) and found that the more expensive devices which provided additional degrees of freedom (namely roll, pitch, and yaw) were not necessary for the applications in this area. Using the Falcon device, students can sufficiently interact with the 3-D environments in the apps described above.

The Falcon is attached to a PC computer by using a standard USB interface. The specifications for the computer are minimal (1.0 GHz processor, Windows [XP, Vista, 7, 8], 128Mb graphics card, DirectX, 1.5 GB hard drive, 512 MB RAM, and a USB 2.0 connection). Device drivers can be downloaded from the Novint website.

3.2 Haptic Software Development Kit

The HSDK Libraries being used in these apps was developed especially for this project by team members in two versions – to integrate with C/C++ environments including the OpenGL graphics library or to integrate with Gamestudio Realtime 3D Authoring System (Gamestudio) (www.3dgamestudio.com). The HSDK is a high-level library that provides easy integration of Falcon haptic functionality into existing graphics application. The main functions of the libraries are to map the haptic workspace, haptic rendering of shapes and force effects. The HSDK can create primitive 3D shapes such as a cylinders, cubes, or spheres, or load a custom shape in STL format. It also includes several custom effects that have been requested by the developers to convey necessary information within the particular lessons (Table 1).

4. DEVELOPING APPS

The development process begins with the identification of a topic and continues until an app is ready for distribution. This process insures the development of consistent, quality applications that can be used for middle school students with visual impairments.

The Software Requirements Specification (SRS) is a document that is used to guide the development of all apps. This document describes the functionality and the best practices that must be consistently applied.

4.1 Developing the Lesson Ideas

The first step in the development process is to work with a lesson designer (typically a teacher) to identify a suitable topic for the application. The main considerations are to ensure the topic lends itself to haptic effects and also there are suitable graphic/haptic objects that can be obtained or developed for each scene.

Early in the project graphic/haptic object (such as the organelles in a plant cell) were developed by a graphic designer. The team quickly found that this was very costly and not necessary, because there are a vast amount of 3D objects that can be purchased for use on the internet. Sites such as turbosquid.com or other free sites had many objects suitable for the lessons and they supplied usable file formats.

After choosing an appropriate lesson idea, the lesson designer is asked to create a Lesson Guide that identifies the national mathematics or science standards that will be covered in the app, briefly explain the learning objectives for the app, and tell how the app can be used in the classroom. After the Lesson Guide is prepared, the lesson designer completes the Software Design Document (SDD). The SDD is a storyboard that explains each scene and gives the graphics, audio, and haptic effects that will be used in the app. This SDD is submitted to the software developer and the lesson designer and software developer iterate on the design until agreement is reached on how the app should function.

¹ www.novint.com

Haptic Effect	Description
3D Regular Shape	Regular shapes (sphere, cube and cylinder) can be defined and sized.
3D Irregular Shapes	Irregular shapes can be defined by a triangular mesh in the STereoLithography (STL) file format.
Textures	Textures can be applied to the surface of shapes using a normalized range -- 0.0 (smooth) to 1.0 (bumpy).
Moving Objects	Objects in the scene can be lifted and moved. Collision detection between objects is supported.
Weight	Weight can be applied when shapes are lifted using a normalized range of 0.0 (no weight) to 1.0 (about 2 lbs.).
Permeable Surfaces and Viscosity	Viscosity can be applied to a shape to allow penetration of the surface and an effect of moving through liquid in the object with the strength of the effect uses a normalized range of 0.0 (least dense) to 1.0 (most dense).
Magnetism & Repulsion	Magnetism can be applied to objects in the scene in order to draw the user toward the object when the cursor position is close to the object. The strength of the magnetism can vary as well as the range when it is applied. Repulsion, the opposite of magnetism, is also supported.
Vibration	Vibration can be applied to any region of a 3D scene or any object. The strength and intensity of the effect can be changed to make the vibration slow or more rapid.
Elasticity	General elasticity acts as if a 3D spring is attached to the grip. The resting position of the spring can be set. The strength of the effect can be set using a normalized range of 0.0 (weakest) to 1.0 (strongest).
Items Leaving Scene	All the objects in the scene can be destroyed using a single function call.
Shape Tracing	A 2D curve constraint allows the haptic interface device's motion to be constrained to a 2D open or closed curve oriented in space. The curves can be chosen from some standard shapes or loaded from a Scalable Vector Graphics (SVG) format file.

Table 1. Effects that can be produced using the HSDK with the Falcon haptic game controller.

4.2 Common Frameworks

There are three different development framework models that can be used – sequential, springboard, and random problem. These provide a starting point for app development. All navigation between scenes in the app is contained in the framework. The programming outline of each scene is present, so to develop a new app, the developer need only insert the specific graphics, haptic effects and audio files. Having a set of frameworks to begin with cut the development time from approximately two months to two weeks. After the SDD has been agreed upon by the lesson designer and the developer, the development can begin. The designer finds suitable objects for the scenes, for example a heart model for the Circulatory System app. This model is purchased and downloaded in a format for 3D graphics (3DS) and a format for haptics rendering (STL). One of the first steps for the development of the haptic application requires the programmer to integrate haptic and graphic rendering into the scenes of the chosen framework. This requires calling on the Falcon HSDK Libraries. After doing this, the audio files are added. This is a very simplified look at the development. For a more detailed explanation of the development of the apps consult Darrah, Murphy, Speransky and DeRoos. [12]

4.3 Using the Effects for Math and Science

For each of the apps, many different haptic effects were chosen to add to the user experience. In all of the apps, 3D objects are presented so that student can move the cursor over the shapes and get a sense of the object. Other effects are also used to provide information through the sense of touch that keeps that students engaged and gives them information that they may not be able to see.

For example, the Exploring the Atom app uses magnetism and texture to teach student the parts of an atom. The app starts by introducing students to the three parts of the atom and how they will feel to the student throughout the app. Each part is represented by a sphere. The electron has a magnetic force and a slightly gritty texture, the neutron has a bumpy feel, and the proton has a smooth feel, but pushes you away. As the student continues to move through the scenes of the app, they encounter first a hydrogen atom with an electron ring. The electron ring is magnetized so that the cursor can get locked into a path and go around the path until they find the electron. In the center of the scene is the nucleus of the atom, with the protons and neutrons. There are also scenes with a carbon atom (Figure 2) and a nitrogen atom so that students can experience atoms with more of each of the parts. Throughout the app, the narration gives information about the science, what the students should be feeling and how to navigate through the scenes.

The Volume of 3D Shapes app uses vibration and elasticity to help students “measure” 3D shapes to compute volume. The students are presented with a problem of making ice cream cones from a cylinder shaped container of ice cream. First, the student is allowed to feel the cylinder shape of the container. The 3D cylinder container is made slightly gritty feeling and

is slightly magnetized so it can be found easily in the scene. The students are also asked to measure the height of the container by finding the vibrating hotspot at the bottom of the container and pressing a button on the controller to be drawn up along the side of the container (using the elasticity effect) to feel the height. The next scene allows them to trace the circumference of the bottom of the container using the trace effect. Other scenes in this app allow them to feel the shape of the ice cream cone (a bumpy cone) and the ice cream scoop (a penetrable sphere with dense viscosity). In each case they also measure these using the same method of find a vibrating spot that allows them to press a button and be moved through a measurement of the object. In this app, students derive the formula for the cylinder and are given the formulas for the cone and sphere to help them solve the final problem (Figure 3).

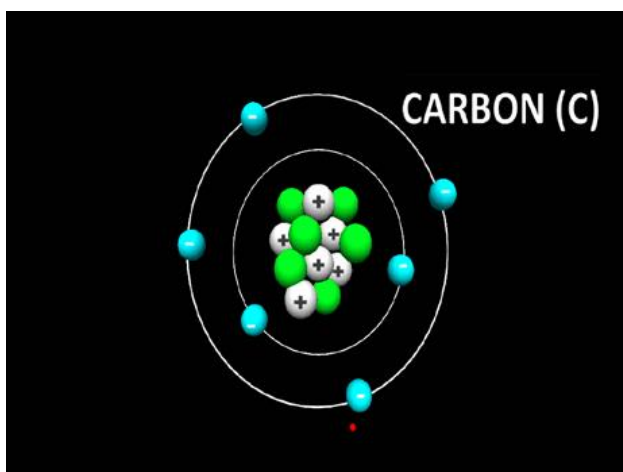


Figure 2. One scene from exploring the atom. The carbon atom with its nucleus and electron rings.



Figure 3. The cylinder container of ice cream and the ice cream cone are shown in this scene. Each of the 3D shapes can be touched and explored.

The Circulatory System app uses the guided tour to explain how blood flows through the various parts of the circulatory system. This technique employs the elasticity effect to gently pull the grip to different regions on the scene as the narrator goes through an explanation.

In the Coral Reefs app, many irregular shapes are rendered to model different kinds of fish and coral. The fish are made bumpy to depict scales and the trace is also employed so that students can trace the shape of the fish.

The weight effect is employed in several of the apps. For example in the Gravity on Planets and the Moon app, a bowling ball is depicted on different planets and the Earth's moon (see Figure 4). The weight of the ball changes depending on the planet on which it is depicted. The ball can be “grabbed” using the controller button and “lifted” to see its weight. This app helps students learn the difference between weight and mass.

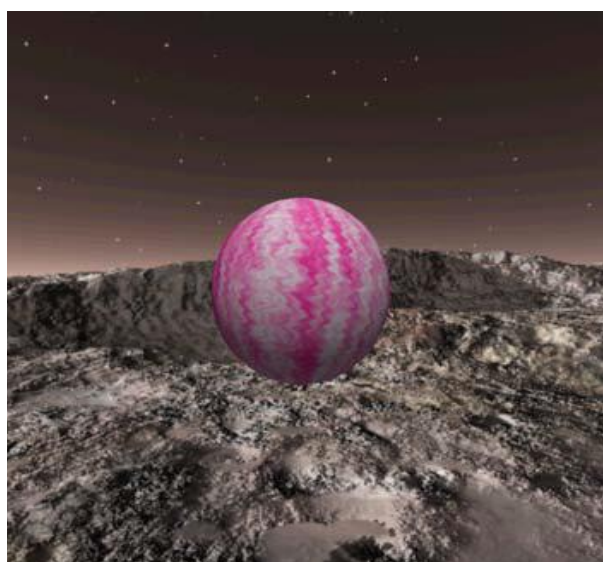


Figure 4. A bowling ball depicted on the surface of the planet Mercury. The ball can be “lifted” using the haptic grip to feel the relative weight.

5. TESTING WITH STUDENTS

The computer applications were tested with students in both an informal and formal setting. This section describes the outcomes of this testing.

In both settings, the pre- and post-tests developed by the lesson designer were used as the instruments. Both

tests had the same content questions, but at the end the pre-test collected demographic data and the post-test gathered impressions of the app. The content questions were short answer, different from the quiz questions in the app. The number of questions on the tests varied based on the content of the app. The pre-test allowed for the determination of student baseline scores. To assure content validity the test content was reviewed by a science teacher, and a table of specifications was developed to map the test questions to the app's learning objectives. In addition, students were instructed to give

an “I don’t know” response if they didn’t know the answer to discourage guessing.

5.1 Informal Learning Setting

Three lessons were tested at Space Camp for Interested Visually Impaired Students (SCI-VIS) in Huntsville, Alabama, USA.

5.1.1 Procedures

The Space Camp director collected student assent forms and parent consent forms so that each party gave agreement to participate in the study.

The procedures used for testing in this setting were as follows. Three test stations (haptic device and laptop with an app) were set up in the testing room. A pre-test station and a post-test station were set up at the far ends of the room. Each student was given the opportunity to try out the haptic device and practice using the Three Dimensional Shapes app before the testing began. At the pre-test station, students were given the pre-test (large font or Braille version) for the apps. After completion of the pre-test, students took turns completing the apps on three app test stations. As a student completed an app they were sent to the post-testing station.

Students wore pendants around their necks indicating which app tests and apps they had completed. Not all students were able to complete all three apps in the four hour test time. There were four adults and two older students helping with the testing and the apps. The students were not assisted with the use of the apps or the tests, except if a technology issue arose.

5.1.2 Demographics of Test Subjects

Twenty students tested the apps. They represented all ranges of visual impairment from mild visual disability to total loss of vision. Eleven students fell in the mild and moderate ranges; nine students were in the severe to profound loss categories; and four students at near total or total loss of vision. The age range of students was ten years of age to 17 years of age with 16 of the students falling in our target grade range for the software (5th through 9th grades).

5.1.3 Results

Significant gains ($\alpha = .02$) from pre-test to post-test were observed on all three labs. Fourteen students completed both Exploring the Atom and Surface Area of a Cube, while nine students completed the Gravity on the Planets App. Students were also asked two Likert scale questions at the end of the post-test about their enjoyment of the apps and using the haptic device. Although their levels of enjoyment varied by app, no student said they did not enjoy the app or using the haptic device. For all apps more than 77% of the students said they either enjoyed the apps or enjoyed the app a lot, while the others indicated that they enjoyed the apps a little.

5.2 Formal Learning Settings (Classroom Testing)

A total of five teachers participated in the testing over two academic semesters. Two were teaching at residential schools for the blind, two worked as teachers of the visually impaired in a typical school setting and one was a typical classroom teacher. The participants for this research were 32 students with various levels of vision.

5.2.1 Procedures

The teachers first collected student assent forms, a parent consent forms and a teacher consent form, so that each party gave agreement to participate in the study. The teachers then allowed the students to work with the Three Dimensional Shapes App to familiarize themselves with the Falcon haptic controller and haptic-based software.

Next, the teacher gave the student the pre-test for the app. The student could take it on paper (using large font or Braille) or the teacher could read and record the answers for the student. The teacher was instructed to make sure not to help or prompt any particular response from the student; simply record responses. Then the students were allowed to work with the app for as long as needed to complete the lesson. Again, the teacher was instructed not to help the student answer questions, only to help if there was a technical issue with the computer or the device. After the student was done with the app (usually around 15-20 minutes), the teacher gave the student the post-test for the app.

Similar to the pre-test, the student could take it on paper (using large font or Braille) or the teacher could read and record the answer for the student and the teacher was instructed to make sure not to help or prompt any particular response from the student; simply record responses. Upon completion, the teacher mailed both the pre- and post-tests back to the researcher for grading. The pre- and post-tests were all scored by one person using a pre-defined rubric to ensure consistency.

5.2.2 Demographics of Test Subjects

The students ranged in age from 11 to 17 years and were in grades 4 through 12, with most students in grades 6, 7, 8, and 9 (the target age group). Only five students fell outside of this range.

Students were asked to self report their vision level. There were three students with no vision loss, ten with mild or moderate loss of vision, eleven with severe or profound loss, and 7 with near total or total vision loss. One student did not report his/her vision level. Eight of the students participated in both sets of testing for all six apps, but most of the students only did three of the apps.

5.2.3 Results

In the Spring of 2013, three apps were tested in classroom setting by four classroom teachers. Student showed significant learning gains on all three apps. For the Exploring the Atom app, the pre- and post-tests were composed of seven open-ended questions with a minimum possible score of 0 and a maximum possible score of 14. Respondents' ($N = 22$) mean pre-test score was 3.10 ($SD = 3.88$) and mean post-test score was 7.02 ($SD = 2.99$). A paired t-test was used to show there was a

significant increase between the pre-test and post-test scores ($p < .00001$). For the Gravity on Planets app, the pre- and post-tests were composed of seven open-ended questions with a minimum possible score of 0 and a maximum possible score of 16. Respondents' ($N = 22$) mean pre-test score was 3.90 ($SD = 2.84$) and mean post-test score was 8.24 ($SD = 3.78$). A paired t-test was used to show there was a significant increase between the pre-test and post-test scores ($p < .00001$). For the Surface Area of a Cube app, the pre-test and post-test was composed of five open-ended questions with a minimum possible score of 0 and a maximum possible score of 11. Respondents' ($N = 23$) mean pre-test score was 2.09 ($SD = 1.76$) and mean post-test score was 4.05 ($SD = 2.56$). A paired t-test was used to show there was a significant increase between the pre-test and post-test scores ($p < .00001$).

In the fall of 2013 and the spring of 2014, three other apps were tested in classroom setting by four classroom teachers. Some of the teachers who previously tested the apps also tested with students in this round of testing. For the Exploring the Plant Cell app, the pre- and post-tests were composed of three, multi-part, open-ended questions with a minimum possible score of 0 and a maximum possible score of 15. Respondents' ($N = 14$) mean pre-test score was 2.21 ($SD = 2.19$) and mean post-test score was 8.71 ($SD = 3.71$). A paired t-test was used to show there was a significant increase between the pre-test and post-test scores ($p < .00001$). For the Blood Cells app, the pre- and post-tests were composed of five open-ended questions with a minimum possible score of 0 and a maximum possible score of 19. Respondents' ($N = 13$) mean pre-test score was 2.92 ($SD = 3.20$) and mean post-test score was 10.08 ($SD = 2.60$). A paired t-test was used to show there was a significant increase between the pre-test and post-test scores ($p < .00001$). For the Circulatory System app, the pre- and post-tests were composed of six open-ended questions with a minimum possible score of 0 and a maximum possible score of 13. Respondents' ($N = 14$) mean pre-test score was 3.33 ($SD = 3.29$) and mean post-test score was 9.67 ($SD = 4.59$). A paired t-test was used to show there was a significant increase between the pre-test and post-test scores ($p < .001$).

6. CONCLUSIONS

These positive preliminary results show promise for the haptic-based apps to support student learning. The effects can be utilized in many different ways to provide information and give students something to hold their attention. The preliminary testing of six apps has shown that they can be valuable classroom materials for middle school students who are blind or visually impaired. Feasibility testing also revealed that the haptic device is easy for teachers to set up and learn to use.

The technology is affordable and there are unlimited possibilities of what can be done with it. Although 20 apps have been developed, there are thousands of other ideas that could be developed into apps. The original intent was to ask teachers to submit ideas and find developers interested in making apps to meet the needs. The framework allows for a starting point for computer

programmers to put together an app without much previous training on the exact software. This innovative technology and software can integrate rich information through the sense of touch to add to the information being provided through auditory and visual means.

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