Augmenting Physics Education with Haptic and Visual Feedback

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Augmenting Physics Education with Haptic and Visual Feedback

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ABSTRACT

For educational purposes, virtual reality (VR) is often used to produce life-like experiences. However, the use of haptic feedback in educational practices for science and mathematics remained understudied. Haptically-enabled science simulations (HESSs) enable students to physically experience the concepts being taught via haptic feedback. We present a study on the effect of a buoyancy HESS designed to aid in the understanding of basic physics concepts. We hypothesize that introducing both visual and haptic feedback of the underlying simulated forces will improve participants understanding. We investigate this hypothesis with a 2 (haptics: yes, no) × 2 (visuals: yes, no) between subjects design user study, where all participants were randomly assigned to one of the four conditions. Participants were given a pre-test of buoyancy knowledge, then instructed to interact with the buoyancy simulation, then given a post-test of buoyancy knowledge. The present study is still in the process of data collection, with 40 out of 60 participants. Preliminary results highlight a significant improvement in performance of participants in the haptic-and-visual condition, while no significant differences were observed in other conditions.

Index Terms: Education—Computer-assisted instruction; Communication hardware, interfaces and storage—Tactile and hand-based interfaces—Haptic devices

1 INTRODUCTION

Virtual reality (VR) systems are commonly used for training and education in various disciplines, including medical [2,7,9,14], industrial [6,13], flying and driving [3,8], and K-16 education [1,5,10]. A common reason for using VR in these training and education scenarios is to enhance the reality of situations that "cannot be accessed physically," including traveling back in time, visiting outer space, and training in life-threatening situations such as fire fighting or surgical training simulations [5].

The effectiveness of VR training and education systems is paramount to their application for future use. Even though it is accepted that VR is beneficial for education, the differential impact of visual feedback and haptic feedback on comprehension is less well understood. The importance of haptic feedback has been demonstrated for surgical training [4,15], however it has remained understudied in science, technology, engineering, and mathematics (STEM) learning environments [12,16].

2 BACKGROUND

2.1 Haptically-Enabled Science Simulations

Elementary school teachers often have limited opportunities for their students to practice complex mechanistic reasoning–including understanding the concepts and laws of physics. These complex and abstract ideas are often thought to be beyond students' grasp, and are subsequently not tied directly to a concrete and directly observable lesson. As a result, such lessons are usually postponed until higher grade levels [11]. The limited STEM education provided to elementary-aged students limits opportunities to reason about the hidden mechanisms responsible for the "how," "when," and "why" of observed phenomena.

Supplementing instructors' teaching materials with suitable haptically-enabled science simulations (HESSs) could aid in an earlier introduction of these ideas and, in return, encourage more exploration of said concepts at an earlier age. Specifically, the use of haptic force-feedback technology can provide a direct physical connection to many of the invisible mechanisms at play for various physical phenomena. HESSs can also tap into educators intuitive physics ideas and help them construct consistent models. This process can improve their teaching of basic physics with their students early on, laying the groundwork for future STEM learning.

2.2 Specific Aims

This study aims to better understand how people learn, and specifically the interplay between haptic feedback and visual feedback for an HESS focused on teaching concepts related to buoyancy. Its intertwined project goals are to:

(1) Add foundational human-computer interaction (HCI) knowledge to guide the design, development, and testing of HESSs.

(2) Isolate and document the haptic influence on the development of teachers specialized content knowledge of forces as interactions.

(3) Study the pedagogical impact of HESSs on elementary preservice teachers.

3 SYSTEM DESIGN

3.1 Equipment

The haptic device used in this study was a Novint Falcon. The Falcon supports three degrees of freedom (DoF) position tracking of its grip: left and right (x-axis), up and down (y-axis), and forward and backwards (z-axis). Refer to Fig. 1 for an image of the device and its DoF. The Falcon can also apply forces in along these three dimensions to the grip, enabling the user to feel the resultant force. The details on rendering haptic forces in our study are described in Sect. 3.2.

The experiment was run using the Unity 5.6.7 engine on an Alienware Aurora R6 desktop computer. The computer had four Intel Core i7-7700 cores (3.60 GHz), 16.0 GB of RAM, an NVIDIA GeForce GTX 1080 GPU, and 64-bit Windows 10. The experiment was displayed on a Dell monitor with a 1680 × 1050 resolution.

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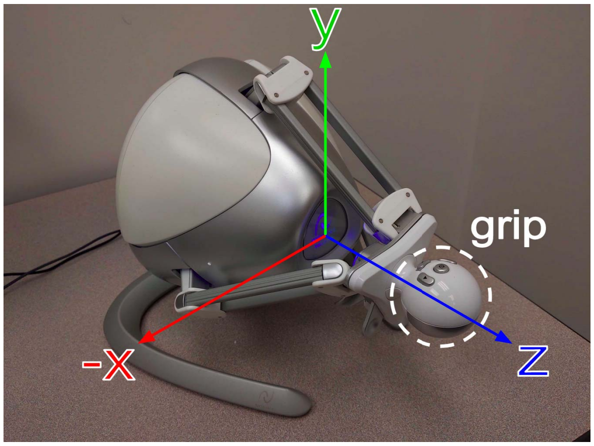

Figure 1: A photo of the Novint Falcon used in our experiments. The user can move the grip (labeled with a white dashed circle) and feel forces applied to the grip in three dimensions.

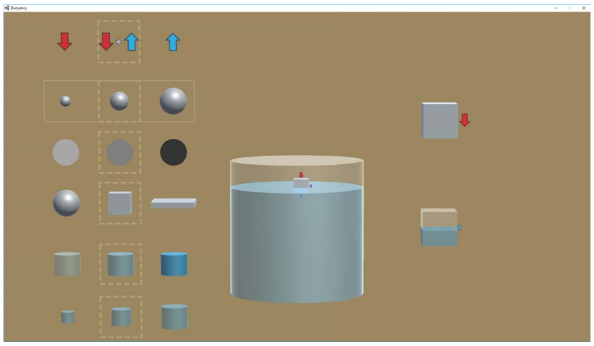

Figure 2: A screenshot of the simulation used in our experiment. The property selection menu is shown on the left side of the screen. In the center are the container, liquid, and buoyancy objects. In this image, the object is set to a cube and is floating near the center of the container. On the right side of the screen is a visualization of the buoyancy object (top) and the volume of the displaced liquid (bottom).

3.2 Buoyancy Simulation

3.2.1 System Dynamics

We created a virtual environment to simulate and visualize different aspects of buoyancy in real time (Fig. 2). The environment includes a liquid in a container, and a buoyancy object. The system models buoyancy based on Archimedes' principle: an object completely or partially submerged in a fluid is acted upon by an upward (buoyant) force with a magnitude equal to the weight of the fluid displaced by the object. If the buoyant force is greater than the object's weight, i.e. the net force is positive and points upward, it will float. If the buoyant force is less than the object's weight, i.e. the net force is negative and points downward, it will sink. The simulation enables the user to move the object in and out of the liquid, drop the object into the liquid, and adjust various parameters–such as the object size, the object density, and the liquid density–while experiencing visual and haptic feedback of the resulting changes in the forces at play in the simulation.

3.2.2 Property Selection Menu

Using the number pad on a keyboard, the user can change various properties of the simulation, such as the object's volume and density. Details of each modifiable property and its options are provided in Table 1. The selection menu can be seen on the left side of Fig. 2. When n property is modified, the simulation is instantly updated with the new setting.

3.2.3 Simulation Interface

The user can move the Falcon device's grip to control a cursor on the screen in a fashion similar to a traditional mouse. Although the Falcon supports 3 DoF, our simulation ignores the *z*-axis, constraining the on-screen motion to 2D in *x* and *y*. The user can press and hold a button on the Falcon grip to pick up the buoyancy object. As the user moves the device while holding the object, the object follows the device position on the screen.

In conditions that include haptic feedback, the net force acting on the object is rendered by the Falcon when holding the object. For example, if the user holds the object out of the liquid, a force equal to the object's weight will be applied. However if the user holds the object under the liquid, the net force of the object's weight and the buoyant force will be applied, which could be an upward or downward force depending on whether the object would float or sink. Since the user is holding onto the Falcon's grip to grab the object, they will feel the force being exerted by the Falcon. Note that this study is only concerned with buoyancy, so haptic forces were only rendered along the *y*-axis.

3.2.4 Visualizations

On the right side of the screen are zoomed-in visualizations of the buoyancy object and the displaced liquid. To visualize the volume of the displaced liquid, a transparent version of the buoyancy object is filled with liquid according to how much of the object is currently submerged.

We also visualize the magnitude of the object weight, buoyant force, and net force using arrows. The arrow is scaled proportionally to the magnitude of the corresponding force. These arrows can be seen in Fig. 2. All three arrows are drawn on the movable buoyancy object, while only the gravitational and buoyancy force arrows are drawn next to the object and displaced liquid visualizations respectively.

4 METHODS

Previous work suggests that haptics and visual feedback may improve learning. Based on this we devised the following hypotheses:

H1 Using the system will improve understanding of bouyancy.

H2 Visual feedback will improve understanding over no visual feedback.

H3 Haptic feedback will improve understanding over no haptic feedback.

H4 The combination of visual and haptic feedback combined will improve understanding over visual or haptic feedback alone.

To determine the effects of haptic and visual feedback on learning buoyancy concepts and to test our hypotheses we performed a 2 (haptics: yes, no) × 2 (visuals: yes, no) between-participant user study approved by the (removed) institutional review board. The experimental design, color coding, and abbreviations used for the four conditions are depicted in Figure 3. The visuals of interest were the rendered force arrows. Participants in the NO and HAP conditions did not see the force arrows on the buoyancy object or the objects on the right side of the scene. The haptic feedback for the Falcon device was turned off for participants in the NO and VIS conditions, however participants still used the Falcon to interact with the simulation.

Property	**Setting 1**	**Setting 2**	**Setting 3**
Rendered haptic forces	Gravitational only	Gravitational and buoyant	Buoyant only
Object volume	Small	Medium	Large
Object density	Low	Medium	High
Object shape	Sphere	Cube	Wide rectangle
Liquid density	Low	Medium	High
Liquid volume	Small	Medium	Large

Table 1: Properties of the simulation and their different settings. Properties in this table are listed in the same order (top to bottom) as in the selection menu (Fig. 2).

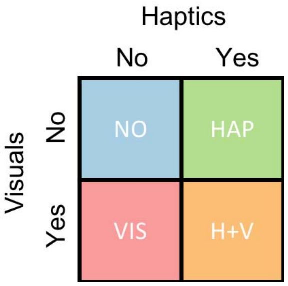

Figure 3: The abbreviations for each of the four between-participant conditions. NO - No haptics and no visuals (blue), HAP - haptics and no visuals (green), VIS - no haptics with visuals (pink), and H+V - haptics and visuals (orange).

4.1 Procedure

Participants were recruited from the (removed for review) community via email, flyer solicitation, and snowball recruitment to participate in a study that tests the effectiveness of an educational application. Upon arrival at the (removed) lab participants were greeted by a Chinese male experimenter and led into a private experiment room containing several desks, computers, the Novint Falcon, and a video camera. Participants completed a checklist confirming that they were eligible to participate (see Section 4.2). Participants then completed an informed consent form and consented to being video recorded.

Participants were then given a verbal overview that the experiment would include taking a questionnaire that assessed current physics knowledge, followed by interaction with a teaching application, and then another questionnaire and demographic survey.

Participants were directed to a desktop computer that administered the buoyancy questionnaire (see Section 4.2) via Qualtrics. Participants spent approximately 15 minutes completing the buoyancy questionnaire.

After completing the questionnaire, participants were asked to move to a neighboring computer where the Novint Falcon and buoyancy simulation were set up. Participants received verbal instructions that they would be interacting with the teaching application and that the experimenter would walk them through basic instructions. The experimenter introduced participants to the Novint Falcon, explained the keyboard and button commands, and described the system features including picking up, moving, and dropping the object into a container of liquid, and selecting different objects, containers, and liquid properties.

Participants were placed in one of the four experiment conditions, NO, HAP, VIS, or H+V. Participants were verbally instructed that they would be given up to 15 minutes to interact with the application and that additional instructions would be given throughout the process. Participants were further asked to describe their actions and thoughts during the process, as well as assumptions and questions about the system. Participants were encouraged to ask questions through the experiment, however some answers were not provided until the end of the experiment. Finally, participants were reminded that they would be video recorded.

The buoyancy simulation consisted of 6 scenes. In scene 1, participants could manipulate object volume. In scene 2, participants could manipulate object volume and object density. In scene 3, participants could manipulate object density and object shape. In scene 4, participants could manipulate object density and liquid density. In scene 5, participants could manipulate liquid density and liquid volume. In scene 6, participants could manipulate all properties.

Scene 1 was designed as a training scene for participants to become acquainted with the interface and keyboard commands and enabled adjusting only the object volume settings. Participants were given verbal instructions to select different settings, and to use the Falcon's grip to grab, lift, and drop the object. Participants completed each action and were encouraged to ask questions about the interface. After participants felt comfortable with the basic commands they were then instructed to press the space bar to enter the next scene. At the start of each scene, participants were reminded that they are to press space to enter the next scene after they have fully explored a scene, at their own discretion. At the start of each scene, participants were also instructed to ”freely explore” the scene. Before entering the next scene, participants were asked what they believe the scene is trying to teach them.

During scene 2 and scene 4 (where the object density and liquid density options are first introduced, respectively), participants were given a description of the settings. For object density, participants were told that the three materials of object were “similar to” cork, wood, and brick; for liquid density, participants were told that the three materials of the liquid were “similar to” oil, water, and mercury. For other scenes, settings were not explained at the start of scene, but an explanation was provided if asked by participants.

In the last scene, participants were instructed to freely explore the scene, and to notify the experimenter when they have fully interacted with the simulation. Participants were allowed to move between scenes at their own pace, untimed.

After interacting with the simulation, participants were instructed to finish the post-test portion of the buoyancy questionnaire. Participants were reminded that the second questionnaire includes similar content to the first questionnaire, and were instructed to complete the questionnaire while reconsidering their responses.

After completing the post-test portion of the buoyancy questionnaire, participants were given a brief demographic survey that collected age, gender, academic focus/major (if applicable), and past physics education. After completing the demographic survey, participants were thanked for their time, debriefed, and compensated.

4.2 Measures

Buoyancy Questionnaire. An assessment (described to participants as “questionnaire”) was created to assess knowledge on buoyancy. The questionnaire consists of a pre-test and a post-test. In the pre-test, participants were instructed to complete a series of questions online. Questions 1-5 on the questionnaire are yes-or-no questions that prompt participants to determine if a described object will float or sink, followed by a free response option that prompts participants to justify their answer. Questions 6-8 on the questionnaire are short response questions that prompt participants to answer a calculation about buoyancy. For example, participants were prompted to calculate the volume of liquid displaced, the weight of liquid displaced, etc.

After completing questions 1-8, participants were shown a page that instruct them to notify experimenter and do not click further.

In the post-test portion, participants were instructed to continue the questionnaire from the page where it was left off. Participants were also notified that the second questionnaire (post-test component) will include similar contents as the first questionnaire (pre-test component), and were encouraged to reconsider previous answers. Questions 9-16 were identical to question 1-8. Question 17-22 are multiple choice questions. Screenshots of two different scenarios are provided for each questions. Participants were prompted to select which object is more likely to float. Question 23-24 are free response questions that prompted participants to describe "the law of buoyancy", and to find a simile for buoyancy.

After completing questions 9-24, participants were shown a page that instructed them to notify the experimenter and not to click any further.

Demographic Survey. A demographic survey was presented at the conclusion of the experiment, before debriefing. The survey prompted participants for age, gender, education, academic major (if applicable), and past exposure to physics in formal education.

4.3 Participants

A total of 40 participants were recruited from (removed for review), faculty, and general public via email and flyer solicitation and snowball recruitment (mean age =20.83, with 24 female, 1 chose not to respond). (NO = 9, HAP = 9, VIS = 9, H+V = 13). Participants were compensated with $10 (USA) gift card for participation. Participants were at least 18 years of age, fluent in written and spoken English, and not majoring in physics, to be eligible to participate.

5 RESULTS

Test scores were graded by two independent graders using the same rubric and had an inter-rater reliability above 90%. Any questions that received conflicting grades were graded by a third grader.

An outlier test was performed on all the pre-test and post-test scores regardless of condition. One outlier (less than 1.5 times the inter-quartile range of all scores) was identified in one post-test score. A participant in the H+V condition scored only 4 points on the post-test and was removed from analysis.

Analysis was performed on the total score, and then the sub scores of 1) multiple choice, 2) written answer justifications, and 3) computation questions.

Analysis was performed with a 4 (Condition: NO, HAP, VIS, H+V) × 2 (Test: pre, post) ANOVA with condition as a between-participant measure and test as a within-participant measure. Planned post-hoc comparisons looking at changes between pre and post test scores by condition were performed using least-squares means with Tukey adjustments.

A distribution of the total pre-test and post-test scores can seen in Figure 4. No significant differences were found between conditions in the pre-test only scores, $F(3,35) = .83$, $p = .48$, $\eta^2 = .07$ suggesting that there was not a significant difference in pre performance between groups.

A significant main effect pre and post test scores was found, $F(1,35) = 4.21$, $p = .05$, $\eta^2 = .02$. Post hoc analysis was performed. A significant performance improvement was found in the H+V condition, $t(35) = -2.46$, $p = .02$ from the pre-test ($M = 13.42$, $SE = 1.00$) to the post-test ($M = 15.21$, $SE = 1.00$). No other significant changes from pre to post test scores were found. See Figure 4.

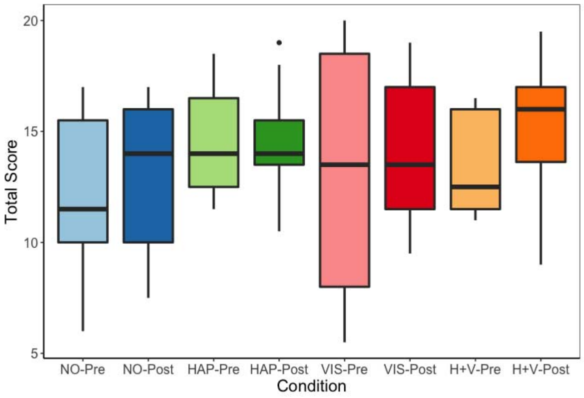

Figure 4: The pre and post test scores for each condition. The pre-test scores are in light colors and the post-test scores are in dark colors. NO - Blue, HAP - Green, VIS - Red, H+V - Orange

	Multiple Choice			
Effect	df	F	η^2	p
Condition	(3,35)	.90	.04	.45
Pre/Post	(1,35)	.00	<.0001	.97
Condition:Pre/Post	(3,35)	1.05	.04	.38
	Free Response			
Effect	df	F	η^2	p
Condition	(3,35)	.06	.003	.98
Pre/Post	(1,35)	3.05	.03	.09
Condition:Pre/Post	(3,35)	.93	.03	.44
	Computation			
Effect	df	F	η^2	p
Condition	(3,35)	.79	.06	.51
Pre/Post	(1,35)	3.33	.008	.08
Condition:Pre/Post	(3,35)	.92	.007	.44

Table 2: ANOVA results for the multipl choice, free response, and computation responses.

Analysis was performed on subsets of the questionnaire to further explore the impact of haptics and visual feedback on multiple choice, free response, and computation questions. No significant main effects or interactions were found. See Table 2.

Planned post-hoc contrasts found a significant improvement in performance in the computation questions in the H+V condition, $t(35) = -2.16$, $p = .04$ from the pre-test ($M = 6.20$, $SE = .73$) to the post-test ($M = 7.07$, $SE = .73$). See Figure 5. No other post-hoc contrasts were significant.

6 DISCUSSION

Significant performance improvements were seen in the H+V condition as measured by performance on a physics assessment from pre-test to post-test. This same performance improvement was not observed in any other condition. The improvement effect may be present in numerous measures of the assessment tool, however a significant improvement was found on the computation questions in the H+V condition. The present finding indicates that applying haptic feedback in combination with visual feedback will improve the effectiveness of physics education.

Potential shortcoming of the present study includes its relatively small sample size and restricted population. The sampled population is largely restricted to the (removed for review) students, which may have led to biased results. Specifically, the educational back-

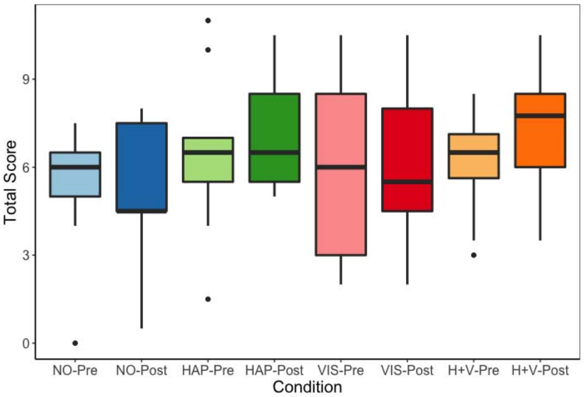

Figure 5: The pre and post test scores for the computation questions. The pre-test scores are in light colors and the post-test scores are in dark colors. NO - Blue, HAP - Green, VIS - Red, H+V - Orange

ground (presented, for instance, by past exposure to physics) and social-economic status of the sampled participants may represent neither the general public nor the target population of education practitioners.

The present study is still undergoing data collection. Further data collection may shed more light on potential interactions between the haptic and visual conditions, or further consolidate present findings.

7 CONCLUSION

The present study hypothesize that:

H1 Using the system will improve understanding of bouyancy.

H2 Visual feedback will improve understanding over no visual feedback.

H3 Haptic feedback will improve understanding over no haptic feedback.

H4 The combination of visual and haptic feedback combined will improve understanding over visual or haptic feedback alone.

Preliminary findings support H1, where there is significant improvement between pre and post test overall, and H4, where only the H+V condition showed significant improvements in performance. This finding shed some light to the effectiveness of haptic technology in science education, which was understudied in past literature.

Implications of the present findings can be applied to primarily educational settings. Future research may aim at validating the finding of the present study with a larger sample sizes and demonstrating effectiveness on the intended population (pre-service educators), as well as the application and integration to pedagogical theories and practices.

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