Effect of haptic feedback on a virtual lab about friction

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Abstract  Background  With the increase in recent years of the utilization of multimedia devices in education, new haptic devices for education have been gradually adopted and developed. As compared with visual and auditory channels, the development of applications with a haptic channel is still in the initial stages. For example, it is unclear how force feedback influences an instructional effect of an educational application and the subjective feeling of users. Methods  In this study, we designed an educational application with a haptic device (Haply) to explore the effects of force feedback on self-learning. Subjects in an experiment group used a designed application to study friction by themselves using force feedback, whereas subjects in a control group studied the same knowledge without force feedback. A post-test and questionnaire were designed to assess the learning outcomes. Results/Conclusions  The experimental result indicates that force feedback is beneficial to an educational application, and using a haptic device can improve the effect of the application and motivate students.

Keywords  Haptic feedback; Science education; Virtual lab; Multimedia education

1  Introduction

In a science curriculum, experimentation can motivate students, and improve the effects of students' learning. Traditionally, students conduct experiments using real-world physical materials and apparatus. The physical environment supplies students with a physical hands-on experience. In recent decades, instructional programs have been developed that can provide students with virtual labs for science experimentation. The virtual environment supplies addition visual information to help students understand science phenomena such as force vectors and field lines, which are invisible in the real world. To achieve tangible manipulation in a virtual environment, researchers have attempted to add a haptic feedback device into the virtual environment, to provide more information though the haptic channel and improve the learning effect.

In recent years, various virtual labs with a haptic device have been developed and evaluated, and researchers have conducted comparison experiments to explore the effects of a haptic device on virtual labs. Existing evidence shows that haptic feedback is beneficial to learning physics knowledge regarding
topics such as gears\(^3\), electricity and magnetism\(^4\), wind force fields\(^5\), and gravity\(^6\). However, there are also some instances where the haptic feedback does not appear to improve the outcome of learning, e.g., regarding such science knowledge as bio-molecular binding-molecular force fields\(^7\) and lever principles\(^8\).

From the above-mentioned literature, it is evident that the results in different experiments are inconsistent. Factors that may affect the consistency of the results include the curriculum procedure, the curriculum domain, the prior experience in the knowledge base, and the cognitive load in the different sensory channels\(^9\). However, there is not abundant evidence to illustrate how these factors affect the outcome of learning in virtual labs.

In this study, a new virtual lab was developed for studying friction, and a low-cost haptic device was integrated into the virtual lab to provide force feedback. An experiment was designed to compare the effects of different conditions (visual-only conditions vs. visual and haptic conditions) on learning friction. The experimental results indicated that providing the haptic feedback in the virtual lab was beneficial to learning but did not affect the subjects' appraisal of the virtual lab.

2 Haptic learning system

Friction is a key concept in the domain of physics. Students learn the concept of friction through experiments in a physics curriculum. Based on a physical experiment, a novel visuo-haptic simulation with a haptic device was developed to teach physics concepts of friction. In this section, details of the haptic device and corresponding interface design of the simulation are presented.

2.1 Haptic device

The haptic feedback of the simulation was conveyed through a 2 degree-of-freedom pantograph device called "Haply" shown in Figure 1. The Haply device is a robust and adaptable open-source hardware development platform for haptic applications developed by Haply Robotics Inc.\(^10\). The Haply device is similar to the Pantograph Mk-II developed by Gianni Campion et al.\(^11\) for mechanical structure and device characterization. A Haply application programming interface (hAPI) for communicating with the Haply is provided for users to control the force output of the haptics device. The output of the Haply device accurately equals the force magnitude set in the software\(^10\). The force feedback can be turned off by cutting off the power on the Haply device. In this mode, the Haply behaves like a computer mouse.

2.2 Interface design

The visuo-haptic simulation was implemented using Unity3D, along with the hAPI for communicating with the Haply devices. Figure 2 shows a screenshot of the visuo-haptic simulation. The software interface consisted of an interaction panel and four parameter panels.

In the interaction panel, a virtual box was rendered on the flat ground and was navigated by the end effector of the Haply device. The bottom of the box was in contact with the ground, and the direction of the box's motion was parallel to the ground. In the bottom-left corner of the interaction panel, there was a panel displaying the value of the friction force. A green arrow indicated the magnitude and direction of the friction force.
In the parameter panels, buttons selectable by clicking a mouse were designed for adjusting parameters of the box and the ground, such as the mass of the box, the contact area between the box and the ground, and the material of the box and ground (wood, stone, ice, and metal). The software simulated the kinetic friction between the box and the ground, and the haptic feedback was provided for users through the end effector of the Haply device. The kinetic friction indexes between these materials were measured by a method provided in a recent study \cite{12}, and the results are presented on a website (https://github.com/mazhuoluo/VRIH/blob/master/Kinetic\%20friction\%20index). The magnitude of the feedback force was calculated based on the parameters set by users in the parameter panels.

3 Experiment design

3.1 Participants

In total, 20 healthy individuals, 17 males and 3 females, were recruited for the experiment. The participants were junior high school students in the second grade, from a high school affiliated with Renmin University of China. The recruited students ranged in age from 12 to 14. The subjects were divided into two teams of 10 students each. One team (V+H team) used a virtual lab with the haptic feedback in the learning section, whereas the other team (V team) used a virtual lab without the haptic feedback.

3.2 Experiment procedure

The procedure of the experiment in our study was composed of four sections: background investigation, learning, examination, and evaluation.

In the background investigation section, subjects were asked to fill out a questionnaire regarding their age and their degree of understanding of the concept of friction, as well as whether they had used haptic devices or virtual lab systems. All of the subjects chosen to continue the experiment had experience in learning with virtual lab systems, but had no experience using haptic devices.
In the learning section, subjects sat in a comfortable chair facing a desktop computer, and interacted with the virtual lab system using a mouse and the Haply device. First, the Haply device and the virtual lab were introduced to the subjects. Subjects were taught how to adjust the parameters of the box and the ground, and how to operate the Haply device to move the virtual object and feel the force feedback. Subjects were allowed 3 min to familiarize themselves with the virtual lab. Then, subjects began to study the concept of friction with the proposed system. A curriculum with material regarding friction was given to the subjects at the same time, and was composed based on an 8th-grade physics textbook. The material consisted of two sections: (1) an introduction to friction and (2) an experiment instruction. By reading the introduction, the subjects could understand the concept of friction. Based on the experiment instruction, the subjects conducted an experiment with the virtual lab to discover the relationship between friction and several factors, and wrote down their conclusions on a paper. Subjects could stop learning once they had understood the knowledge regarding friction, or had spent 30 min in the section.

In the examination section, subjects took a paper-based test of the knowledge regarding friction. Ten questions regarding friction were chosen from a recent study[^12], and some parameters in these questions were modified. These questions were all multiple-choice questions, and each question had four choices. Three questions (concept questions) concerned the concept of friction and could be understood only after reading the curriculum material, and seven questions (experiment questions) concerned factors impacting the magnitude or direction of friction and could be learned only though using the virtual lab. Therefore, the paper test could evaluate the outcome of learning with the software and the ability to understand the textbook.

In the evaluation section, subjects filled out an evaluation questionnaire regarding the virtual lab and learning process, as shown in Table 1. Subjects provided ratings on a scale from 1 to 5 for five questions related to the support of learning, the enhancement of motivation, the global evaluation of the program, and so on. One point meant disagreement and five points meant agreement. Finally, subjects spent some time discussing issues in the entire procedure, and the conclusions were recorded.

| Table 1 Evaluation questionnaire regarding subjects’ feelings on the experiment |
|-----------------|-----------------------------------------------------------------------------|
| Index | Questions |
| Q1 | I think that I spent shorter time on learning how to use the application by myself. |
| Q2 | I think that using the application enhanced the motivation of learning. |
| Q3 | I think that the application is helpful for me to learn friction. |
| Q4 | I think that the application reduces the cognitive load for me. |
| Q5 | I think that the experience to use the application is good. |

4 Results and discussion

4.1 Paper-based test

In the examination section, subjects could obtain one score for each question in the paper-based test, and the results of the test are presented in Figure 3. We calculated the mean of the concept question scores and the experiment question scores of the two teams. A two-tailed t-test was employed to evaluate the difference between the two teams in the paper-based test. The difference in the concept question scores was not significant between the V+H team and V team (p=0.784), indicating that the two teams had the same ability to read and understand the text. Meanwhile, the V+H team (mean=5.4) performed better than the V team (mean=4.6) in the experiment question test. There was a statistically significant difference between the two teams (p=0.032<0.05), indicating that the difference in the results of the experiment question test
arose from the haptic feedback in the virtual lab, and that adding the haptic feedback into the virtual lab improved the effect of learning friction concepts in physics.

In scientific experimentation with manipulations that offer touch sensory feedback, an additional (touch) sensory channel of information is provided, allowing subjects to receive further information regarding the manipulations involved\[9\]. One key advantage of this additional (touch) sensory channel is that it initiates an offloading cognition mechanism through which the cognitive load on an individual's working memory during learning decreases, thereby supporting the development of a more complex understanding. In the learning section, instead of observing the magnitude of friction on the screen through the visual channel, subjects chose to feel it through the haptic channel. Therefore, some information that ordinarily traveled through visual channels was instead transferred through the sensory channel of touch. The cognitive load for the visual channel of subjects in the V+H team decreased without increasing the total cognitive load, leading to a better effect in learning the concept of friction.

### 4.2 Evaluation questionnaire

As for the results of the evaluation questionnaire, there was no difference between the two teams in the five questions, and the scores of all of the questions were above 4 points, as shown in Figure 4. This indicates that the two teams gave a positive appraisal to the virtual lab and the experiment process. There are two reasons that may explain the results. First, according to the results of the background investigation, most subjects had not interacted with a virtual environment with a haptic device. Subjects were unfamiliar with the virtual lab and were very interested in it, leading to improved motivation for both teams. Second, the same visual information was transmitted to both teams and was adequate for helping subjects understand all of the knowledge regarding friction, leading both teams to believe that it was effective to learn friction using the virtual lab.

Because there was no reference to the virtual lab in this study, the scores of these questions were affected by individual differences. The high scores do not indicate that the virtual lab had good performance, but rather demonstrate that the performance of the system with haptic feedback was similar to that of the systems without haptic feedback. Subjects could give different appraisals of both learning conditions only after experiencing both learning conditions. However, if subjects experience both learning processes, i.e., with and without haptic feedback, the degree of understanding of the knowledge of friction before the former experiment will be different from that before the latter experiment. In one study\[13\], subjects learned different knowledge in different scenarios in a virtual lab. The procedure assured that the prior knowledge was the same in the
different conditions before the subjects began to learn. Nevertheless, the common issue of this learning procedure was that different learning contents resulted in different learning difficulties. This could affect the outcomes of learning, and destroy the consistency in learning content under different conditions.

According to the feedback from subjects after the experiment, we summarize two key suggestions regarding the system and experiment procedure. One suggestion is that more material should be supplied in the virtual lab. Subjects indicated that they were willing to experience material that they were familiar with. The other suggestion is that a texture simulation should be added to the system to enhance the reality. A realistic simulation leads to a link between the prior experience and experiment.

4.3 Limitations

There are still some limitations in our study. First, there was no prior test before the learning section in our experiment procedure. As there was no prior knowledge of friction, subjects would get a low score in a prior test, and the results would not be significant for this study. For this reason, the prior test was canceled. Second, the curriculum material and the test paper are written in Chinese, and thus our study may be different in results from others written in English. Chinese subjects benefited from reading the concept as written in Chinese when learning the knowledge, and they were under little pressure insofar as understanding the text. Prior studies\textsuperscript{[13,14]} had used a declarative question test to evaluate subjects’ understanding of knowledge. The answers truly revealed the outcome of the learning in the virtual lab, but this process of analysis is difficult for other researchers to reproduce. In consideration of that, an objective question test was chosen in our study, as an evaluation method for the experiment procedure.

5 Conclusions

In this study, a virtual lab with a haptic feedback device (Haply) for learning the concept of friction was presented, and an experiment was conducted to investigate the learning effects of a visuo-haptic condition and visual-only condition. It can be seen from the experimental results that adding the haptic feedback into the virtual lab can enhance the outcome of student learning, but the learning condition did not affect the appraisal of the virtual lab. In the future, we will optimize our virtual lab by decreasing the load of the visual channel, or by optimizing the haptic rendering by adding vibration components into the haptic device. With a better virtual lab, a new experiment will be conducted with more subjects, to investigate the effect of the haptic device on the virtual lab.

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