Haptically Enhanced User Interface to Support Science Learning of Visually Impaired

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Abstract. The primary purpose of this study is to evaluate the overall quality of haptic user interfaces designed to support various science learning activities in order to obtain usability and performance data. The result showed that haptic interface could significantly affect impaired students' user performance. Audio & Tactile interface can produce significantly better user performance than the Tactile interface. Meanwhile, the learning effect could be greatly enhanced and students enjoyed the hands-on experience very much. This study should provide invaluable empirical data and some insight for the future research.

Keywords: haptic, tactile, visual impairment, interface.

1 Introduction

According to National Health Interview Survey in 2008, more than 25.2 million Americans reported experiencing vision loss [1]. Statistics from Braille Institute showed that vision problems affect 5% (about 5 million) of school-age children, ages 3-5 and 25% (12.1 million) of school-age children, ages 6-17 [2]. Although visually impaired, they have the right to receive the same science education as other people with normal sight. However, one big challenge for visually impaired students is that: most of the materials (e.g., textbooks, graphics, etc) for science learning are still visually based. According to Patton & Braithwaite [3], almost 90% of science teachers who teach the visual impaired students teach science class mainly based on textbook. White [4] argued that science textbooks generally present science concepts in the most abstract formats and mathematical models. But since visually impaired students' main sensory channels are tactile and auditory, textbooks are, needless to say, insufficient in meeting such needs. Meanwhile, visually impaired students' preconceptions about natural phenomena may differ from the accepted scientific concepts [5]. Considering that most science concepts are intrinsically abstract, visually impaired learners often have difficulty connecting abstract science concepts to sensory experience-based knowledge [6, 7].

To help visually impaired students learn more efficiently and directly, haptic technology has been increasingly applied across multiple domains [8-10]. Haptics utilizes tactile feedback to manipulate a variety of touch-based sensorial experiences. Different methods can be employed to realize haptics, such as forces, vibrations, and motions [11]. Some researchers propose that haptic perception (e.g., force,

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vibrotactile and thermal), combined with audio information, can improve visually impaired students' ability to understand scientific concepts [12, 13]. Moreover, visually impaired students can better acquire information through haptic sensations [14]. With sensorial feedback, visually impaired students can conceptualize and retain scientific mental models more easily [15]. Even more importantly, hands-on haptic-based science learning experiences instill greater confidence and increase critical problem solving [9]. Despite recent advances in haptic research, research opportunity still exists, especially in the usability analysis of haptic applications.

The primary objective of this study is to evaluate the overall quality of haptic interfaces designed to support various science learning activities (e.g., menu selection, navigation and recognition of molecular structure and force, etc.) in order to obtain usability and performance data, as well as to refine the design guidelines for haptically enhanced science learning systems.

2 Haptic Interfaces

The Molecular Properties Module (MPM) is a haptically enhanced science learning system that provides visual, haptic, and auditory feedback for students with visual impairments to learn molecular concepts such as molecular structure and intramolecular force. MPM was developed to facilitate haptic science learning for students with visual impairments and supports two key tasks: molecular structure recognition and intramolecular force recognition.

2.1 Molecular Structure Recognition

Molecular Structure Recognition supports Tactile, Audio, and Audio & Tactile interfaces. Each haptic interface supports the display of three molecules (CO_2, H_2O, and BF_3) as Two-Dimensional (2D) Ball & Stick molecular models (Fig. 1). Each molecule supports haptic force feedback to enable users to trace around the edges of the model using a haptic device.

The tactile interface adds tactile feedback to a group of atoms within the model. This tactile feedback allows a user to further distinguish one atom from another within a molecular model. For example, H_2O contains three atoms – one Oxygen (O) and two Hydrogen (H) atoms – and the connecting sticks. When the user touches the Oxygen atom, a smooth tactile effect is rendered; when the user touches either

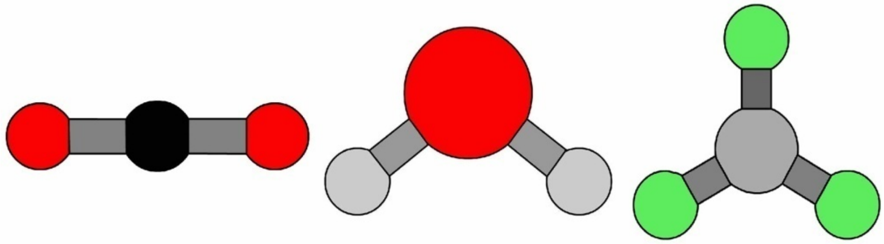

Fig. 1. Molecular structure recognition: *left* (*CO_2*), *middle (H2O)*, *right (BF3)*

Hydrogen atom, a bumpy tactile effect is rendered; when the user touches any connecting sticks, a sandpaper tactile effect is rendered.

The Audio interface adds audio feedback to each atom within the haptic molecular model. A pitch is played every time the user's cursor comes into contact with an atom. As with the previous H_2O example, when the user touches the Oxygen atom, a medium-pitched audio effect is played; when the user touches either Hydrogen atom, a high-pitched audio effect is played; when the user touches any connecting sticks a low-pitched audio effect is played.

The Audio & Tactile interface combines both audio and tactile modalities described above into one interface type.

2.2 Intramolecular Force Recognition

Intramolecular Force Recognition supports two molecules (CO_2 and CS_2) as molecular spring models. Each model allows the user to manipulate (i.e. grab) the atoms surrounding the central atom. For example, the user could manipulate the Oxygen (O) atoms in CO_2 and Sulfur (S) atoms in CS_2. Gravity Wells provide a haptic sensation of the delicate balance of attractive and repulsive forces between atoms in the molecule. A gravity well is a haptic tool that automatically snaps the user into the center of an area when the user's cursor is within a predefined pull radius.

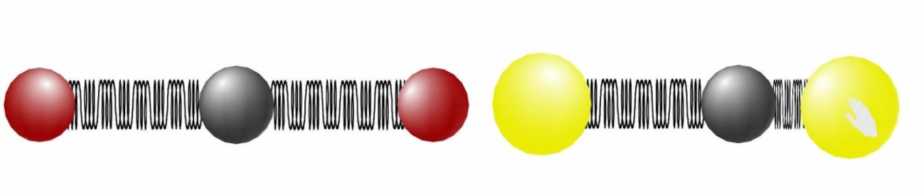

Fig. 2. Spring model for intramolecular force recognition: *left* (CO_2), *right* (CS_2)

3 Methods

3.1 Participants

Twelve participants were recruited from Arkansas School for the Blind in Little Rock, AR. Participants were recruited by instructors at the school and were monetarily compensated for their voluntary participation. There were 5 female and 7 male participants whose mean (M) age was 14.2 years (Standard Deviation, SD = 2.0). All participants had little or no experience with haptic interfaces and haptic devices.

3.2 Apparatus

Hardware includes a Dell PC with a 3.4 GHz Pentium R and 1.0GB of RAM, up to 2 Novint Falcon haptic devices. Software includes Adobe Flash CS3 for visual rendering and a C/C++ Novint SDK for haptic rendering to develop the software. Haptic features were multithreaded, graphics were rendered at 60 Hz, and haptic control was updated at a rate of 1 kHz.

To evaluate the effect of haptic interface, multiple interface types, and haptic interaction methods were developed for students with visual impairments. This study supported 2 key tasks and 4 interface types, as shown in Table 1.

Haptic Interface Evaluation Surveys were designed. They consisted of two questionnaires, one for each key task. Each questionnaire evaluated user preference in regards to the interface types supported by a particular task as well as user comments for each individual interface type supported by each task.

NASA Task Load Index (TLX) was used to measure the workload that participants experienced. It contains six subscales measuring mental demands, physical demands, temporal demands, performance, effort, and frustration. All items were rated on a 10-point scale.

3.3 Independent Variables

The Molecular Structure Recognition task contained only one independent variable: haptic interface. Three haptic interfaces were provided: Tactile interface, Audio interface, and Tactile & Audio interface. In the Intramolecular Force Recognition task, no independent variables were manipulated.

3.4 Dependent Variables

Dependent variables include user performance measurement and user behavior measurement. Key task questionnaires were also utilized to determine interface preference as well as suggestions, improvements to each interface type for the 2 key tasks. Performance Measurements includes workload, task completion time, and Pass/Fail marks (success rate).

To measure user behavior, a Cursor Trajectory Management System (CTMS) was developed in order to collect and store all user cursor behavior throughout each scenario. The CTMS measures data at an interval of approximately 20 milliseconds. A Position Data Analysis (PDA) was conducted on the collected user behavior data. The user's cursor positional data was subdivided into zones to quantify proportions of the user's total cursor activity/behavior.

- **Error Region (ER):** Region(s) surrounding *Stability Region*(*s*) or inside a 2D haptic object. Signifies that the user is not near to any haptic object and is considered poor user behavior.
- **Stability Region (SR):** Region(s) surrounding Trace Region(s). Signifies that the user is very near to a haptic object, within about 10-20 pixels, and is considered good user behavior.
- **Trace Region (TR):** Region(s) closest to haptic object(s). Signifies user interaction with a haptic object and is considered perfect user behavior.

Positional Data were aggregated and proportionally divided to describe the user's total actions for a particular scenario:

- **Error Region Proportion (ERP):** Proportion of total user activity within the ER region(s) of a particular interface.
- **Stability Region Proportion (SRP):** Proportion of total user activity within the SR region(s) of a particular interface.

- **Trace Region Proportion (TRP):** Proportion of total user activity within the TR region(s) of a particular interface.

3.5 Procedure

Prior to the experiment, each participant was required to complete a Consent Form as well as a Demographics Form. Next, each participant was required to complete a Haptic Training Session, which could provide a foundational understanding and sensibility of the Novint Falcon haptic device as well as haptic virtual environments. After the training session, the participant then participated in two uniquely designed key tasks. The sequence of key tasks, haptic interfaces, and scenarios were counterbalanced to remove the learning effect as much as possible. Each scenario was conducted as follows: A participant read a scenario description outlining what haptic objects would be present as well as the scenario goal. During this time, a participant could ask any relevant questions – as long as it did not reveal sensitive information regarding how to go about completing the scenario goal. Participants were told that each scenario had no time limit, though a 10 minute cut off point was enacted if necessary. Finally, participants were made aware that if they felt that they had satisfied a particular scenario's ending condition prior to reaching the time limit, they could say "Done." Upon each scenario's conclusion, participants were asked to complete a NASA TLX questionnaire regarding the completed scenario's cognitive workload. Additionally, upon each key task's conclusion, participants were asked to complete a User Preference Questionnaire to obtain user preference and comments in regards to each interface type within a key task. Table 1 provides a detailed description of each Key Task.

Table 1. Key task description

Task	Description	Pass Condition
Molecular Structure Recognition	To feel a Ball and Stick Model of a molecule. The model has 3 interfaces. When finished, please say "I'm Done" and draw the molecule you just felt.	The user must correctly draw the molecular model (# of atoms, and geometry).
Intramolecular Force Recognition	To feel the intramolecular force between atoms within a molecule for 2 molecules. Locate an atom at first, then use the ACTION button to grab and move the atom to feel the force. When finished, please say "I'm Done" and tell the result of force comparison.	The user must answer that CS2 has a greater intramolecular force

4 Result

4.1 User Performance

In the Molecular Structure Recognition task, the average success rate was 72.2%. ANOVAs were conducted to determine the effect of haptic interface on success rate, workload and task completion time. For Success Rate, significant effect of haptic interface was found ($F_{2,22} = 4.53$, $p < 0.05$). Further analyses showed that success rate in the Tactile & Audio interface (M = 92%, SD = 29%) was significantly higher than that in Tactile interface (M = 42%, SD = 51%). However, there was no significant difference in success rate between Tactile interface and Audio interface (M = 75%, SD = 45%), or Audio interface and Tactile & Audio interface.

No significant effect of haptic interface was found for workload and task completion time in the Molecular Structure Recognition task. However, the mean of workload in Tactile & Audio interface (M = 3.72, SD = 1.54) was higher than that in Audio interface (M = 3.42, SD = 1.36), which was higher than that in Tactile interface (M = 3.26, SD = 1.47). The mean of Task completion time in Tactile & Audio interface (M = 72.89, SD = 40.02) was shorter than that in Audio interface (M = 82.19, SD = 42.22), which was shorter than that in Tactile interface (M = 84.04, SD = 47.28). In the Intramolecular Force Recognition task, participants reached an average success rate of 66.7%.

4.2 Behavior Performance

ANOVAs were conducted to determine the effect of haptic interface on Error Region Proportion (ERP), Stability Region Proportion (SRP) and Trace Region Proportion (TRP) in the Molecular Structure Recognition task. No significant effect of haptic interface was found for behavior performance. However, ERP in Tactile & Audio interface (M = 36.79%, SD = 17.86%) was smaller than that in Tactile interface (M = 41.29%, SD = 24.19%) and Audio interface (M = 41.16%, SD = 21.54%) on average. TRP in Tactile & Audio interface (M = 34.37%, SD = 12.83%) was bigger than that in Tactile interface (M = 30.49%, SD = 16.92%) and Audio interface (M = 30.64%, SD = 15.04%) on average. But SRP were almost the same in the three interfaces: Tactile interface (M = 28.22%, SD = 8.84%), Audio interface (M = 28.2%, SD = 8.74%), and Tactile & Audio interface (M = 28.84%, SD = 8.28%). In the Intramolecular Force Recognition task, participants finished the task with an average 22.54% ERP, 62.47% SRP, and 14.99% TRP.

5 Discussion

Since there were three haptic interfaces in the Molecular Structure Recognition task and only one in the Intramolecular Force Recognition task, the two tasks would be discussed separately. For the Molecular Structure Recognition task, the focus is the effect of the haptic interface. For the Intramolecular Force Recognition task, the focus is the user performance and the applicability of the haptic application.

5.1 Molecular Structure Recognition

Effect of Haptic Interface on User Performance. Result showed that haptic interface had a significant effect on success rate, which was significantly higher in Tactile & Audio interface (M = 92%) than that in the Tactile interface (M = 42%). Success rate in Tactile & Audio interface also had a larger average value than that in Audio interface (M = 75%), but it is not significant.

This result indicates that the Tactile & Audio interface provides more information for user with visual impairments. The Tactile & Audio interface, in addition to haptic force feedback, provides tactile and audio feedback. The combination of force, tactile, and auditory feedback must enhance the user's conception of the molecular structure, leading to better performance. The relevant shorter task completion time in Tactile & Audio interface (M = 72.89) compared to the Tactile (M = 84.04) and Audio interfaces (M = 82.19) further supports that the Tactile & Audio interface produces better user performance.

User Preference Questionnaires indicated that 12 out of 14 participants preferred the Tactile & Audio interface. User comments indicated that the combination of tactile and auditory feedback facilitate ease of use when tracing molecules, feeling and recognizing individual atoms, and visualizing an entire molecular shape.

However, more information also means more cognitive workload. The result showed that participants had relevantly higher workload in the Tactile & Audio interface (M = 3.72) than the Tactile (M = 3.26) and Audio interfaces (M = 3.42). Two participants that did not prefer the Tactile & Audio interface commented that the combination of force, tactile, and audio feedback caused confusion and disorientation during the task. Such a level of cognitive workload can affect the user's concentration and can decrease usability and potentially limit haptic applications. As such, if users have difficulty processing multiple sensorial feedbacks, resulting confusion or disorientation can produce negative effects. For example, higher levels of cognitive workload can cause users to easily tire and lose concentration, limiting the applications effectiveness. Therefore, to create a user-friendly and accessible haptic application, more research is needed to establish the relationship between cognitive workload and acceptable sensorial modalities within a haptic application.

Effect of Haptic interface on User Behavior. Haptic interface showed no effect on user behavior. Although interface type could significantly affect user performance, the difference was not large enough to affect user behavior. However, on average, user behavior showed the smallest ERP and largest TRP in the Tactile & Audio interface among the three types of haptic interfaces. Because TRP and SRP represent good and perfect user behavior, relevantly larger TRP and smaller ERP signifies that the Tactile & Audio interface conditions produce optimal user behavior per task instruction, supporting the hypothesis that multiple modalities can lead to greater interface usability. However, since the effect is not significant, more research is needed.

Haptic Interface Usability Limitations. Although most participants preferred the Tactile & Audio interface, some participants commented that the audio was not systematically designed and that auditory pitch information was, at times, confusing. Considering that the visually impaired may have greater sensitivity and sensibility in receiving and processing auditory information, more research is needed to define user-friendly audio design for those with visual impairments.

Some participants also commented on the difficulty of navigating and locating haptic objects within some interfaces. More specifically, it seems as though these participants had difficulty in developing accurate mental models of the two dimensional environments in order to correctly navigate and locate haptic objects, as well as determine their haptic cursor location relative to the haptic objects within the environment. To better meet the requirements of the visually impaired, a more intuitive navigation should be designed to ensure that users can build accurate mental models of the 2D environment. As a possible solution, perhaps one button on the haptic device could be utilized to automatically return users to a specified area within the haptic environment in the event that the user is lost.

5.2 Intramolecular Force Recognition

In the Intramolecular Force Recognition task, participants finished the task with an average success rate of 66.7% (8 out of 12). The average ERP, SRP and TRP were 22.54%, 62.47% and 14.99%, respectively. Result showed that most participants could perform the task with satisfactory performance and stable user behavior. About 77.46% (SRP + TRP) of the user behavior was efficient. The task also showed a very good learning effect: Questionnaires before the task showed that all of the participants had no concept of the intramolecular forces between the atoms within the CO_2 and CS_2 Molecules. After the task, however, 10 of the 12 participants could distinguish the intramolecular forces and describe an accurate conception of the force. This indicates that the haptic features (i.e. force feedback, gravity wells) within the haptic interface were able to aid students with visual impairments in developing accurate conceptions of intramolecular forces. User Preference Questionnaires indicated that users liked the spring model of the intramolecular force, indicating that the gravity well and force feedback haptic features could enhance user understanding of the intramolecular force between atoms. However, more research is needed to define the intensity of the force, as some participants commented that the force was too weak, while others said it was too strong. Likewise, more usability research should be conducted to determine the optimal haptic interface design elements to greater facilitate intramolecular force conception for users with visual impairments.

6 Conclusion

This study investigated the effect of haptic interface and the learning effect. The result showed that haptic interface can significantly affect user performance as well as the learning effect of users with visual impairments. Moreover, the visually impaired students enjoyed the hands-on experience very much. However, the study also found some haptic interface design limitations, which necessitate further research in order to improve haptic user interface usability. This study should provide invaluable empirical data and some insights to the future research of haptic user interface design.

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