Haptic Paradigms for Multimodal Interactive Simulations

2021
The Journal on Technology and Persons with Disabilities

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Abstract

Touch is often omitted or viewed as unnecessary in digital learning. Lack of touch feedback limits the accessibility and multimodal capacity of digital educational content. Touchscreens with vibratory, haptic feedback are prevalent, yet this kind of feedback is often under-utilized. This work provides initial investigations into the design, development, and use of vibratory feedback within multimodal, interactive, educational simulations on touchscreen devices by learners with and without visual impairments. The objective of this work is to design and evaluate different haptic paradigms that could support interaction and learning in educational simulations. We investigated the implementation of four haptic paradigms in two physics simulations. Interviews were conducted with eight learners (five sighted learners; three learners with visual impairments) on one simulation and initial results are shared. We discuss the learner outcomes of each paradigm and how they impact design and development moving forward.

Keywords

Blind/Low Vision, K-12 Education, Research & Development

Introduction

Touch is a powerful tool for learning and accessibility (e.g. Klatzky et al.). Touch-based learning experiences are beneficial for all students and are particularly critical for individuals with visual impairments (VI). For digital educational resources, touch-based, haptic technology is essential in advancing inclusive interactive learning. Commercially available touchscreens, such as tablets and smartphones, are uniquely multimodal, capable of displaying visuals, providing audio, and conveying haptic information through vibrations. Effectively leveraging vibrations on mobile devices could benefit learners with diverse needs by adding a haptic modality of interaction with digital content, e.g., graphics.

The role of vibrations on mobile platforms has been used primarily to convey tertiary information, such as alerting users to incoming messages. However, research has shown that vibrations can have broader applications including support learning, navigation, and daily tasks for individuals with VI (Klatzky et al.; Gorlewicz et al.; Giudice et al.). Specifically, vibrations can aid users in understanding static graphics such as basic shapes (Tekli, Issa, and Chbeir; Tennison and Gorlewicz 2016), graphs (Giudice et al.; Palani et al.; Tennison and Gorlewicz 2019), and maps (Poppinga et al.).

Despite its potential benefits for all learners and its availability in commercial hardware, vibratory feedback is not commonly used in educational content. This is in part due to a lack of design guidance on when and how to meaningfully use vibrations in static and dynamic content. In this work, we investigate the use of vibratory haptics in multimodal interactive science simulations. We share outcomes from our initial design and implementation of vibratory haptics for two simulations on mobile devices, and exploratory interviews with sighted and visually impaired learners. Findings indicate challenges and potential next steps for advancing haptics for multimodal interactive learning resources.

Discussion

Simulations

Our learning context included two physics simulations, *John Travoltage* and *Balloons and Static Electricity*, from the collection of PhET Interactive Simulations (PhET) (see *fig. 1*). These simulations were chosen for their open-source code base, and existing auditory display features, including interactive description (auditory description display) (Smith and Moore), and sonifications (the use of non-speech sound to convey information (Tomlinson et al.)). They also represent a comparatively simple (*John Travoltage*) and a more complex interactive experience (*Balloons and Static Electricity*) while addressing the same physics topic (static electricity). Additionally, PhET Interactive Simulations are widely used by teachers and students worldwide. Enhancing these simulations with research-based vibratory haptics has the potential to result in immediate benefits for many learners.

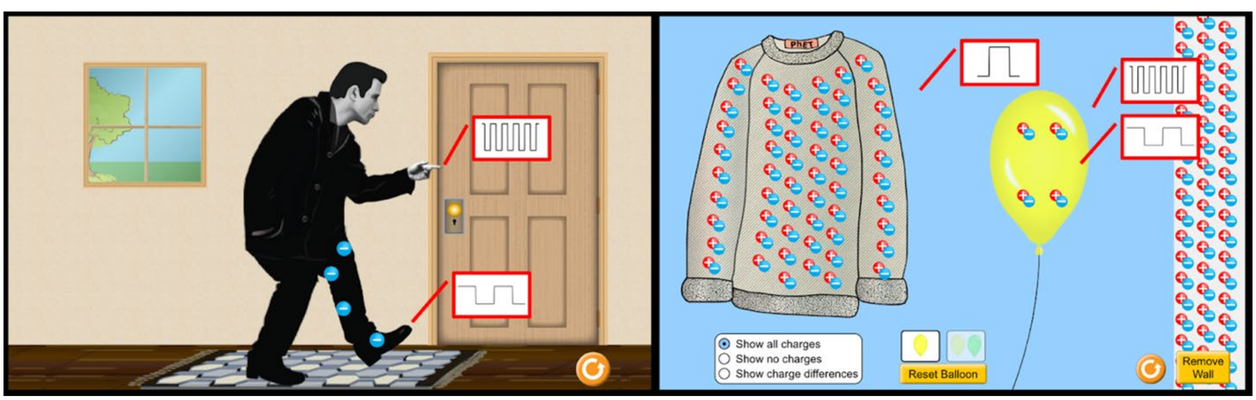

Fig. 1. Examples of Vibratory Implementations for PhET Simulations John Travoltage (left) and Balloons and Static Electricity (right).

Design of Haptic Paradigms

We first designed haptic displays for each simulation. Each physics simulation has a central object (John in *John Travoltage*, and the Balloon in *Balloons and Static Electricity*) akin to a protagonist in a story. There are interactive features of the object the learner can interact with (you can rub John's foot on the rug, and you can move the Balloon onto the sweater or to the wall). Through interaction, the state of the object can change (rubbing John's foot on the rug or the Balloon on the sweater results in a transfer of negative charges onto John or the Balloon, so John or the Balloon can become negatively charged). This change in the object's state can result in changes across the simulation, such as a negatively charged John getting shocked as charges are discharged through a nearby doorknob, and the negatively charged Balloon attracting to - moving across the room to - a positively charged sweater.

Vibration can be used to convey different kinds of feedback, or meaning, to learners, and how learners interpret the vibrations could differ based on the combination of modalities (visual, auditory, and/or haptic) perceivable to the learner simultaneously. To investigate the different kinds of meanings vibrations could convey in the simulations, and how these were perceived and used by learners with and without VI, we designed a set of four haptic paradigms to implement for each simulation. Each paradigm represents one type of meaning that vibrations can convey: 1) Objects; 2) Interactives; 3) Local State changes; and 4) Global State changes (as described in Table 1). The individual paradigms were not intended to represent a complete "final" design; we anticipate that a blend of vibratory feedback from two or more paradigms will ultimately result in the most effective and preferred user experience. The paradigms were to allow for exploration of how learners perceived and made use of each isolated type of vibratory feedback, to provide insights into the potential ways each could be leveraged to achieve an interaction or learning goal of the simulation.

Table 1. Summary of the Four Haptic Paradigms Investigated.

Paradigm	Description	*John Travoltage* Implementation with Vibration Parameters
Objects	Touching the main objects results in vibratory feedback. This paradigm emphasizes the presence of each object, no dynamics are represented by vibrations.	Body ([100, 100], slight pulse) Carpet (Default Vibration) Arm ([25, 25], continuous) Leg ([50, 50], continuous)
Interactives	Moving interactable objects results in vibratory feedback. This paradigm emphasizes interactive objects, no state information is provided when the simulation changes during interaction.	Moving the arm ([25, 25], continuous) Moving the leg ([50, 50], continuous)
Local State Changes	Performing actions which change the simulation results in vibratory feedback. This paradigm emphasizes changes made to the simulation from direct user interaction.	Rubbing the foot against the carpet to generate charge (Default Vibration)
Global State Changes	Highlight changes made to the simulation itself with vibratory feedback. This paradigm emphasizes the resulting state of the simulation after user interaction.	Particles have accumulated on the body ([100, 100], slight pulse) Particles are being discharged to the doorknob ([200, 100], jittery pulse)

Development and Implementation of Haptic Paradigms with Android and iOS

We implemented the haptic paradigms on Android and iOS platforms. We used a Samsung Galaxy Tab S3 tablet (Android) which generates vibration with a coin cell actuator, and an iPhone 11 (iOS) which generates vibration with a linear actuator. Implementing the design paradigms on two platforms allowed for investigation of the differences in affordances related to vibration control, feel, and interaction during use with and without the native screen reader application.

Both platforms allow the developer to control the duration of actuation (which creates the vibration) and the duration of rest (no vibration). Additional options for customizing vibrations on both platforms are available, such as intensity on Android and iOS, and sharpness on iOS (see Weber and Saitis). We used the duration of vibration and rest to generate the vibrations within our four haptic paradigms.

A couple of key differences were discovered between Android and iOS during development. First, Android allows developers web access to vibration triggers inside of browsers, but iOS does not. To trigger vibrations in a custom context on iOS, a dedicated app must be built. Second, the native screen reader for Android, TalkBack, lacks support for the Accessible Rich Internet Applications (ARIA) attribute *valuetext*, which allows for the delivery of text strings (non-numeric descriptions) for the range of sliders, progress bars, and spin buttons.

Challenges were encountered for the combined use of vibratory haptics and screen reader software for both platforms. Potentially most impactful for the design of vibratory haptics supporting access for people with VI is the manner in which screen reader devices handle and intercept touch interactions. For example, freely exploring the onscreen representations through touch, and experiencing vibratory feedback to sense the size and shape of an object is limited, as the touch events are intercepted by the screen reader application and interpreted within its gesture options as taps or swipes, shortening any vibration pattern to the duration of the gesture. This interception occurs when using both TalkBack and VoiceOver, though we found it to be most restrictive using VoiceOver. Additionally, auditory description display implemented in PhET simulations is fully supported for VoiceOver, mobile VoiceOver, NVDA, and JAWS. The lack of support for ARIA *valuetext* decreased the description available to leaners with VI. Because of this, non-visual access to PhET simulations is best using mobile VoiceOver compared to TalkBack, though access to the haptic paradigms was more limited on iOS than Android.

Exploratory Interviews with Learners Using Haptics on Mobile Devices

We conducted semi-structured think-aloud interviews (Lewis, 1982) with visually impaired and sighted learners on an Android tablet with the *John Travoltage* simulation to understand the affordances of each of the paradigms. Five sighted individuals (M = 22.4 years) and three individuals with VI (M = 22.3 years) volunteered to be interviewed (see Table 2 for complete demographics). All learners with VI utilized screen reader software in their daily technology use and did not utilize the visual display during the interviews. All participants were from a midwestern university and compensated with a $25 gift certificate for their time. Interviews took up to one hour to complete. This study was approved by the relevant institutional review board.

Table 2. Participant Demographics.

#	Sex	Age	Visual Impairment
1	Male	22	None
2	Male	23	None
3	Female	21	None
4	Male	25	Retinitis Pigmentosa
5	Female	22	None
6	Male	24	None
7	Male	23	Retinitis Pigmentosa
8	Male	19	Lebers Congenital Amaurosis

The structure of the interviews was similar for all learners, but the interviews with learners with VI were more discussion-based and facilitated than those with sighted learners as all three learners with VI used exclusively iOS, none were familiar with TalkBack. Learners with VI had less access in these exploratory interviews to the vibrations due to standard screen reader operation. We discuss our next steps to mitigate these challenges and increase access to both robust haptic and auditory display in the Conclusions section. For ease of evaluation and comparison of the paradigms, learners with VI could switch between having sonifications and no sonfications as well as switch between paradigms at their own pace. We present findings from both learner groups, with qualitative perceptions being the focus of the learners with VI and performance data being the focus of the sighted learners.

Participants were asked to narrate their experience in exploring each paradigm of each simulation, describing their process in understanding the purpose of the haptics and providing feedback regarding the effectiveness of the haptic renderings. The interviewer observed each learner's interactions and asked clarifying questions, seeking to understand how the learner was exploring, identifying, and interpreting the set of vibrations within each paradigm, as well as their needs and preferences.

During interviews, learners were asked to explore the implementation of each paradigm on *John Travoltage,* both with and without sonifications. For an overview of the auditory description display (used by learners with VI only) and sonifications and their design, see Tomlinson, et al. The interviews with sighted learners were counterbalanced such that half of learners explored all four haptic paradigms on *John Travoltage* without sonifications first, followed by exploring all four haptic paradigms with sonifications.

Results

Learners using visual display and haptic display, with and without sonifications. The five sighted learners were able to complete their first use of the simulation and articulate the main concepts in under a minute (M = 49.48 seconds; *min* = 30 seconds; *max* = 60 seconds). Participants who received the haptic versions of *John Travoltage* with sonifications first (N = 3) were marginally faster (48 seconds, 56 seconds, and 30 seconds) than the individuals who received *John Travoltage* without sonifications first (55 seconds and 60 seconds). All participants confirmed that they were able to feel the vibrations and hear the sonifications well.

Several criteria were used to evaluate the learners' interactions with the corresponding simulation version. These criteria were: 1) identifying the correct number of vibration patterns; 2) articulating the purpose of the vibration; 3) ease of interaction; and 4) finding personal value in the vibrations presented.

When using the Objects paradigm, all learners found value in the vibration patterns and could articulate their purpose, despite not being able to accurately identify all four vibration patterns present. The arm and leg vibrations were the most commonly recognized (with sonifications: 4 of 4 participants; without sonifications: 3 of 4 participants). One learner (in both conditions) discovered the vibration used to represent John's body, but could not articulate it as such. Only one learner (no sonifications) explored the entire on-screen sim area and discovered the rug vibration.

Learners reacted less favorably to the Interactives paradigm. While some learners (with sonifications: 3 of 5 participants; without sonifications: 2 of 5) liked the vibrations associated with moving the arm and leg, all learners across both sonifications and no-sonifications conditions remarked that the vibrations were not meaningful to them. Three of five learners in the sonifications condition indicated that the vibrations were frustrating or redundant with both sonifications and visuals.

The Local State Changes paradigm was the most well-liked haptic paradigm, meeting all learners' expectations for functionality. However, all learners remarked that the simulation felt incomplete with this paradigm. All learners could articulate the purpose of the vibrations (to generate charge with the foot on the rug) and a majority of learners found this to be valuable interaction feedback (with sonifications: 5 of 5 participants; without sonifications: 4 of 5 participants).

The Global State Changes paradigm was also well-liked by learners, but similarly viewed as being an incomplete implementation. Most learners (with sonifications: 4 of 5 participants; without sonifications: 4 of 5 participants) felt this representation was valuable, although the presence of a single continuous vibration pattern to indicate John had accumulated charge was an area of contention. Very few learners liked the implementation of the accumulated charge vibration pattern as implemented (with sonifications: 1 of 5 participants; without sonifications: 2 of 5 participants). All learners initially interpreted this continuous vibration of John's body while having charge as a bug, as all other vibration patterns encountered in the interview were discrete.

Learners using auditory description display and haptic display, with and without sonifications. All three learners with VI could articulate the purpose of the simulation. Enabling sonifications seemed necessary for successful exploration and navigation of the simulation for these learners -- haptics alone was not sufficient. During the first walkthrough of the simulation, two learners requested assistance from the interviewer regarding the operation of TalkBack.

During the exploration of the Objects paradigm, learners did not like the short, choppy vibrations associated with interactive movements. While sighted learners receive continuous vibratory feedback while their finger remains on the model's arm, leg, body and the rug, learners with VI receive abrupt vibrations due to event handling by Talkback. One solution we explored to address this was toggling the screen reader on and off. While turning off the screen reader allowed learners with VI to organically find each component through sound and vibration, learners had difficulty using the interactive components across all haptic paradigms without screen reader assistance. Overall, learners did find value in the proposed solution and desired a way to reconcile the screen reader limitations to receive vibration while interacting with objects.

Similar to sighted learners, learners with VI found the Local State and Global State Changes paradigms to be the most valuable in terms of conveying pedagogical content. However, the learners stressed the importance and the value behind being able to spatially map the simulation itself. All learners with VI desired a version of the simulation that could be "paused" in order to find the various components and spatially explore the content.

Learners with and without sight also shared feedback on specific vibration patterns implemented in the paradigms. Continuous patterns (operating between 100-200 Hz; described as "buzzy") were deemed uninteresting or overstimulating during prolonged exploration. Overwhelmingly, learners enjoyed the pulse vibration implemented to convey the discharge of particles from the finger to the doorknob in the Global State Changes paradigm. The vibration pattern for the foot rubbing against the rug in the Local State Changes paradigm, although "buzzy," was also liked as it met learners' expectations of the interaction. This creates a strong case not just for more varied vibrations, but those that suit the context of the action.

Conclusions

Our goals for this work were to investigate how vibratory haptics can be used to support or enhance interaction with multimodal interactive science simulations. We designed four haptics paradigms for two physics simulations, each paradigm representing one type of feedback (or meaning) the vibrations could convey. We implemented these across two platforms, discovering challenges most notably for the use of auditory description provided through native screen reader software, and access to our custom haptic vibration designs. Overall, all eight participants interviewed indicated that vibratory feedback was an exciting interaction feature and made a meaningful addition to the simulation.

Future Work

From our initial design of haptic paradigms, we will investigate further ways to blend the paradigms to align with the visual and auditory scaffolding of the simulation, supporting initial interaction, and sensemaking with the objects and relationships represented (Podolefsky, Moore, Perkins, 2013). To support learners who could benefit from an exploration of the spatial location of objects with vibratory cues, we will also investigate supporting the addition of a “layer” of vibrations that provide information regarding the objects and interactive elements on-screen. These explorations will include designs with more variations of vibrations, vibration patterns closely aligned with all sonifications, and a systematic exploration of variants of continuous feedback (e.g., fading over time, frequency, etc.). We have also found that the haptics design has interesting overlaps with the sonification design. In the future these two features may pair well together in the design process, and haptic display may benefit from having sound and sonification designers involved in the creation and evaluation of vibration patterns.

The incompatibilities between screen reader applications and vibration capabilities have led us to begin development of self-voicing (with description provided through the browser) with custom gesture control. We plan to investigate this alternative access to haptics vibrations, auditory description display, and sonifications with learners with VI, to inform our haptic designs and potential additional features to complement existing auditory description display provided through screen reader software.

From these investigations, we aim to develop foundational knowledge regarding the perceptual factors that influence effective design of haptic displays, current and emerging possibilities for implementation of haptic displays, and best practice guidelines for the use of haptic displays within interactive learning resources - to create more accessible learning resources for all students.

Acknowledgements

This material is based upon work by the National Science Foundation Grant No.s 1845490 (DRL), 1621363 (DRL), and 1814220 (DRL). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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