Multimodal STEM Simulations: Design, Development, and Evaluation

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Abstract
Interactive simulations can be highly effective STEM learning tools, but may be inaccessible to users with vision impairment and other disabilities. We are developing multimodal versions of the popular PhET sims, that supplement the visual interface with complete auditory descriptions accessible by screen reader software, and sophisticated and engaging auditory displays. We follow rigorous user-centered design principles, and employ participatory design methods, followed by extensive iterations of user evaluations. These multimodal PhET sims should provide STEM tools to a diverse range of learners.

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Interactive simulations, web accessibility

ACM Classification Keywords
K.3.1 [Computers and Education]: Computer-assisted instruction; K.4.2 [Social Issues]: Assistive technologies for persons with disabilities.

Introduction
Simulations (sims) provide an effective interactive method for students to explore and learn about real-world phenomena [4]. As these tools become widely-used in a variety of classrooms, their limitations to functional access for students with visual impairments

John Travoltage Sim

A man is standing on a rug near a door. Moving his leg causes his foot to rub on the rug, transferring electrons from the rug to John. Moving his arm towards the doorknob discharges electrons - an exciting "zap."

Navigation and Description
The descriptions accessible by screen reader include a Scene Summary, e.g., "His arm is close to the doorknob, and he's ready to swing his leg to rub his foot on the rug." Reading on provides descriptions of the current state of the leg or arm (e.g., "Slider position (number), foot off rug"). Navigating to the leg or arm slider allows users to move the leg or move the arm

While interacting with the leg or arm sliders, descriptions provided as alerts indicate the important state changes: "Slider position 5, electrons on body 55."

…continued…

become increasingly apparent. Creating alternative access methods, especially for supporting science education (where concepts are often represented visually) presents a challenge for educators and researchers [11].

Interactive sims can be structured to directly support collaboration between students, as they work together to gather evidence and understand the underlying models and concepts [1]. Combining appropriate visual accommodations [3] with additional modalities (e.g., audio, tactile) may allow students with mixed abilities to collaborate and learn from the same interactive sims [10].

Accessible Simulation Development

The PhET Interactive Simulations Project has more than 140 free math and science simulations (sims), including 55 built in HTML5 [12]. Ongoing work by the PhET team includes supporting alternative means for navigation, designing text descriptions for screen readers, and development of sonifications (non-speech auditory cues) to highlight important information. The simulation *John Travoltage* [8] is one of the first sims to include all of these enhanced features, integrated together holistically to provide a broadly accessible STEM simulation. Many more such multimodal sims are in development.

Simulation Description

In *John Travoltage* (described in sidebar) the keyboard navigation, text descriptions, and sonifications come together to support a complete experience for users with vision impairment. The user can interact using the mouse, the keyboard, or both. The feedback is visual, as well as auditory, including screen reader speech, plus non-speech sonifications, earcons, and auditory icons. These are all integrated to allow multiple ways to access the sim.

Navigation and Text Description Design

Making the underlying architecture of the sims accessible leverages the Web Content Accessibility Guidelines (WCAG 2.0) and WAI-ARIA Authoring Practices [9]. A complete text-based description for each sim exists in a navigable HTML structure called the Parallel Document Object Model (PDOM), which updates dynamically and represents all components of the visual sim.

Understanding dynamic changes that result from student interactions is important to helping a student internalize a concept and build meaning. Combining real-time alerts, navigable HTML5 structure, and dynamic state information accessible at the user's command creates a non-visual user experience that allows users to explore and interact with the sim and to connect their interactions with the changes in the sim's visual representations. Iterative evaluation helps to optimize the description. Extensive examples of PhET's approach to the design and implementation of navigation and text description are available [13,14].

Sonification Design

Some dynamic movements and changes are either too difficult to describe well or too complex to describe concisely through text. Sonification uses non-speech audio to convey information [7] and provides an additional resource for presenting complex details (e.g., a balloon drifting is easier to represent through a drifting sound than a long sentence describing its movement). Sonification research has found that

***John Travoltage* sim**, *continued…*

Sonification
Each time his foot rubs on the carpet, an auditory icon of fabric rubbing plays; as electrons enter his body, small bubble pops play. Accumulated electrons move around in his body, and are represented via a quiet "buzzing." As the number of electrons in his body increases, the buzz becomes louder.

Moving John's arm plays small ratcheting sounds; the pitch increases as his hand moves closer to the doorknob. Built-up electrons discharge when his hand is close enough to the doorknob, and is represented four ways: a shock, the bubble sounds leaving, an alert saying that a "discharge occurred," and a longer description telling how many electrons are left and how close the arm is to the doorknob.

auditory displays can leverage metaphors to support concept mappings [15] and improve recognition and recall of data [6].

Different types of sonifications can highlight state changes or provide simple interaction feedback in the sim. For the design process, sound designers and developers on our team work together to build quick prototypes using SuperCollider, Ableton, and the Web Audio API. Initial mappings are informed by educators on the PhET team, and in weekly meetings the team provides feedback and designs are refined.

Accessible Sim Design Challenges

PhET has developed an approach for designing accessible sims. In practice, each sim presents unique design challenges, which can be different across modalities. For example, early work sonifying the sims *Ohm's Law* and *Resistance in a Wire* attempted to design the audio for both in a similar manner. Both sims contain an equation, and use sliders for manipulating equation variables. Initial evaluations with students resulted in two different types of preferred, easily understood auditory displays – reflecting differences in the underlying content being conveyed (*current* in one sim and *resistance* in another). Meanwhile, the navigation and description design process was very similar between the sims.

Addressing the Workshop Themes

Collaborative Learning and Inclusion
Designing accessible learning tools is complex, as it requires a multidisciplinary group to successfully design and implement an interaction which provides effective cues, supports the learning goals, and allows for access to information through a diverse set of modalities.

After iterating on the design using the expert feedback as guidance, we work with different groups of students to understand how well each of the pieces are working together and independently. One goal of this work is to create sims which can foster collaboration between students who have vision impairment and those who do not. We are planning a classroom deployment of the sims for further evaluation.

Design Education and Training
PhET sims are widely used by students across all levels, and we use both user-centered design and participatory design activities during development. Expert screen reader users have helped improve the text description; and novice users highlight the need to support simple interaction and navigation. In addition to standard usability scales like SUS [2] or UMUX [5], we have developed a user experience scale for evaluating appeal, understandability, and ease of use for auditory displays ("BUZZ"; submitted to CHI'18 LBW).

Concluding Thoughts

These multimodal sims being developed by PhET and the Sonification Lab offer a new level of accessibility for interactive STEM learning tools. The technical underpinnings, the design of all modalities, the integration and evaluation, must be considered carefully, to support collaborative tools for a diverse group of learners.

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