Design and Evaluation of a Multimodal Physics Simulation

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1. Introduction

Digital learning resources are becoming increasingly interactive. These resources create opportunities for new learning experiences that can be collaborative and self-directed for students across age groups (Renken et al.). When integrated into the classroom, which typically includes students with and without disabilities, digital learning resources consisting only of visual representations may fail to meet the needs of a diverse audience. Enhancing these resources to include multiple modalities for input and presentation can broaden access for learners.

In this paper, we present the design and evaluation of a multimodal physics simulation (a complex interactive digital learning resource) layered with visual display, multi-component auditory displays (verbalized text descriptions, sound effects, and sonifications), and alternative input capabilities. We aim to create a single simulation with multiple modality 'layers' (Ayotte et al.) capable of being accessed at once or in different combinations to meet the needs of individual users. We designed, developed, and evaluated the multimodal simulation from an iterative, universal access perspective (Obrenovic, Abascal, and Starcevic), leveraging prior work in interactive simulations, descriptions (Smith), and auditory display evaluation (Tomlinson, Noah, and Walker).

2. Multimodal Design of John Travoltage Simulation

2.1 Interaction Design

The PhET physics simulation John Travoltage ("Sonification John Travoltage") (Fig. 1) consists of a man, John, standing on a rug with his hand reaching out towards a door. Rubbing his foot on the rug results in the transfer of negative charges from the rug onto John's body. John's arm can be moved in a 360-degree circle, resulting in his hand being closer or farther from the doorknob. Learners from elementary school through college can use the foot rubbing and arm moving interactions to explore the relationship between the amount of charge on John's body and the distance of his hand from the doorknob that results in discharge/shock.

2.2 Visual

Figure 1 Screenshot of PhET sim John Travoltage.

John is a black-and-white semi-realistic character striking a playful pose (arm and leg appearing poised for action) in a bright, full-color, room. John, the small rug he is standing on, and the door are in the center of the simulation's play area. Negative charges that can collect on John's body are visually represented as small blue balls.

2.3 Auditory

2.3.1 Sound Effects & Sonification

Multiple types of sound effects and sonifications, listed in Table 1, were designed to support visual and non-visual sim experiences. Sound is displayed using Web Audio and PhET's sound library Tambo.

Sim Feature	Mapping
Foot Rubbing	Carpet rubbing sound (Auditory Icon)
Charge Transfer	Number, pitch increases/decreases as number increases/decreases (Sonified Earcon)
Charges on Body	Static-like, increasing number increases volume and playback rate (Sonification)
Arm Rotation	Ratchet, pitch increases as hand-doorknob distance decreases (Sonified Auditory Icon)
Discharge	Electrical Zap (Auditory Icon)
Shock	"Gazouch" (Speech)

Table 1. Sound mappings to features in John Travoltage sim.

2.3.2 Description

Description can be accessed using screen reader software to support non-visual learning experiences. Dynamic description provides always-available description of the current state of the sim. As learners interact with John's arm or leg, they are provided with position values and real-time alerts. Descriptions highlight the key relationships: amount of charge and hand distance from doorknob. With John's leg, position values indicate when "Foot is rubbing on rug" and when "Foot off rug," and alerts indicate charge transfer, e.g., "Electrons on body: 3." For the arm, descriptions indicate distance from doorknob, regions and landmark positions, changes in direction, and progress towards or away from doorknob. Description is structured using PhET's description framework, and is designed and implemented using a Parallel DOM.

3. Evaluation of Multimodal Design

As part of an iterative design process, we utilized rounds of semi-structured interviews with learners with disabilities (visual impairments or intellectual and developmental disabilities (I/DD) (Tomlinson et al.) and without disabilities from primary school age to adults, to inform the design of all sim features. We included feedback from teachers, content experts, and expert screen reader users. To evaluate later design stages, we conducted semi-structured interviews with five adult learners with visual impairments as well as three children and three college students without visual impairments.

3.1 Semi-structured Interviews

All interviews began with 10 minutes of free exploration of the sim. Then, participants answered a series of open-ended questions about their experiences and interpretation of: sim navigation, description, and sounds. Last, participants completed three surveys: a subset of questions from the BUZZ (Tomlinson, Noah, and Walker) audio user experience scale (for sound aesthetics); a 4-question usability scale, UMUX (Finstad) (for overall sim experience); and a demographics and technology use survey.

4. Results

4.1 Description + Sound Effects/Sonifications. Five adult screen reader users with visual impairments, self-described: low-vision (2) or blind (3), used the sim with no visual display available. Participants rated the aesthetics of the sim (BUZZ scale) as a 25.8 (SD=2.3) out of 28. They also rated the overall usability of the sim (UMUX scale) as 20.2 (SD=4.3) out of 24. Four of the participants specifically mentioned liking how the sounds and descriptions worked together to help them understand what was happening. From open-ended questions, all reported the sounds and descriptions as being useful, and most (4/5) commented positively on description clarity.

4.2 Visual Display + Sound Effects/Sonifications.
Three children (12-13 years old) and three college students, all with no visual impairment, used the sim without descriptions available. Participants rated the sound aesthetics of the sim (BUZZ scale) as a 20.7 (SD=5.2) out of 28. They also rated the overall usability of the sim (UMUX scale) as 21.5 (SD=2.5) out of 24. The college students consistently rated the sim higher and expressed a more positive opinion on the usefulness of the sounds in enhancing the learning experience, while the children were more neutral on sound usefulness. One college student said the sounds make the overall experience with the sim more “immersive”, “interesting”, and “fun”, while one child (13-year old) expressed that the sounds do not necessarily add usefulness to the sim, but feel more like a natural part of it. All learners explored the sim fully and described relationships between amount of charge and arm/hand location. All students made relevant interpretations of the sound mappings, though not necessarily the exact mapping intended by the designers. For example, one student (12-year old) described the arm rotation (ratchet) sound as like a “winding toy,” while another student (college student) described the same sound as a “cranking.” Both learners indicated the sound was present to provide feedback on arm location changes.

5. Discussion and Conclusion

All eleven participants used the same sim, though they accessed different combinations of modalities during exploration. All were able to effectively use the sim and explored the key relationships in the sim. Some difficulties related to the relative volume of sounds in the auditory display were found. When sound effects/sonifications were perceivable to learners, they indicated understanding of the sound/feature mappings. All learners indicated that, in general, they enjoyed the sim, and many indicated the auditory modality was helpful.

We also encountered challenging design decisions while creating the multimodal sim. Some challenges were specific to each modality. For example, refining the interactions, visuals, and descriptions to each scaffold learners to explore the key concepts, refining description to be concise and understandable across age groups, and ensuring sound effects/sonifications were cohesive. Other challenges arose from the intersection of two or more modalities, such as designing sound effects/sonifications to layer with and complement both visuals and description – simultaneously. Ensuring a coherent experience across all modality layers required coordinated efforts across an interdisciplinary team. Though complex, design and evaluation of this multimodal sim further strengthens the case for developing inclusive educational tools that meet the needs of wide range of users.

6. Works Cited

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