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A Multimodal Physics Simulation: Design and Evaluation with Diverse Learners

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Abstract

We present a multimodal physics simulation, including visual and auditory (description, sound effects, and sonification) modalities to support the diverse needs of learners. We describe design challenges and solutions, and findings from final simulation evaluations with learners with and without visual impairments. We also share insights from completing research with members of diverse learner groups (N = 52). This work presents approaches for designing and evaluating accessible interactive simulations for learners with diverse needs.

Keywords

Multimodal; evaluation; interactive simulation; inclusive design; learning; visual impairment

Introduction

Digital learning resources, such as simulations, are ubiquitous and provide opportunities to expose learners to content in uniquely innovative and effective ways (D'Angelo et al.). Digital learning resources are becoming increasingly interactive, providing ways for learners to directly engage with content and creating opportunities for new learning experiences that can be collaborative, immersive, self-directed, and enjoyable for students (e.g., Renken et al.).

Inclusive design approaches seek to create technology with the capability to adapt to meet the needs of users (Ayotte et al.), including the full range of human diversity. Students are most commonly educated in classrooms that include students with and without disabilities (NCES), and interactive digital learning resources need to be able to support all learners within a classroom. While it is common to emphasize visual representations to present content, organization, and navigation in interactive learning resources, expanding these resources to include multiple modalities for display and input can broaden access and effectiveness for learners (Dubois and Vial; Levy and Lahav).

In this paper, we present the design and evaluation of a multimodal physics simulation (sim), a complex interactive digital learning resource with layered multimodal features including visual display, multi-component auditory display (verbalized text descriptions, sound effects, and sonifications), and alternative input capabilities. Our aim was to create a sim with multiple modality 'layers' (Ayotte et al.) capable of being accessed at once or in different combinations to meet the needs of individual learners in the moment. Our efforts extend existing practices in image description (e.g., Keane and Laverentz), align with standards for alternative input (King et al.), and build upon methods for designing and evaluating auditory cues (Barrass and Kramer). We designed, developed, and evaluated the multimodal sim from a universal access perspective

(Obrenovic et al.), using an iterative design process, and leveraging our prior work in interactive simulations (Moore et al.), descriptions (Smith), and auditory display evaluation (Tomlinson et al., "BUZZ").

Multimodal Design of John Travoltage Simulation

Interaction Design

The PhET physics sim John Travoltage ("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. Depending on the amount of negative charges on John's body and the distance of his hand from the doorknob, the electrons can discharge – transferring to the doorknob and 'shocking' John. Science learners from upper elementary school through college can explore the relationship between the amount of charge on John's body and the distance of his hand from the doorknob that results in a discharge/shock.

Fig. 1. PhET Sim John Travoltage.

Learners can navigate and interact with the sim using cursor-based interactions (e.g., controlling an onscreen cursor with a mouse, touchscreen, or related assistive device), touch interaction with a touch-screen device, or focus-based interactions (e.g., controlling onscreen focus using a keyboard, switch, or related assistive device). The arm and leg are implemented as sliders (input type range) as described in Moore, Smith, and Greenberg (Moore et al.).

Visual Display

John is depicted as 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 central. A window looking out onto grass and a tree are off to the left. Negative charges that can collect on John's body are visually represented as small blue balls.

Auditory Display

Sound Effects and Sonifications

Sound effects and sonifications (Walker and Nees) were designed for John Travoltage (Table 1) to support visual and non-visual sim experiences. The audio design presented interaction feedback for body movement (arm and leg), charge changes (charge transfer, discharge, and shock), and a charge state (charges on body). These cues reinforced states represented in the visual display and the description. Sound is played using Web Audio (Adenot and Wilson) and the PhET sound library ("Tambo").

Table 1. John Travoltage Sound Mappings

Sim Feature	Sound Description	Auditory Display Type
Leg swing, slider	Carpet rubbing sound	Auditory Icon
Hand position, slider	Ratchet, pitch increases as hand-doorknob distance decreases	Sonified 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
Discharge	Electrical Zap	Auditory Icon
Shock	“Ouch” and “Gazouch”	Speech
Reset All	Quick rising and falling arpeggio	Earcon

Description

Descriptions can be accessed using screen reader software to support non-visual learning experiences and are structured using PhET’s description framework (Smith), designed (Hung; Moore et al.) and implemented using a Parallel DOM (Smith et al.). The Parallel DOM provides rich document and interaction semantics, and keyboard access aligns with typical interaction of an accessible web page. Our descriptions and interaction patterns are tested and refined with the screen reader software NVDA, JAWS, and VoiceOver.

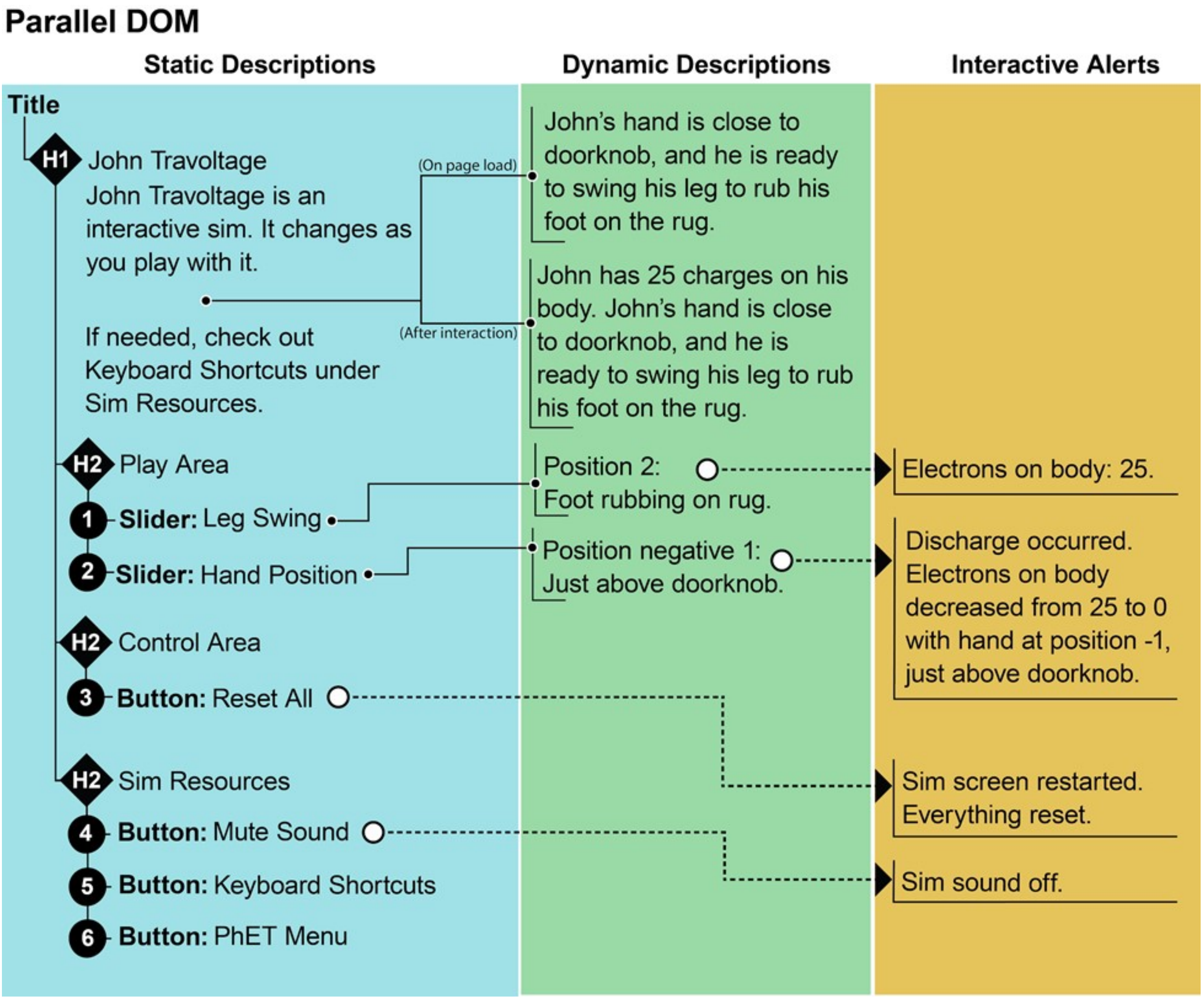

Fig. 2. Parallel DOM View of John Travoltage.

Descriptions include static and dynamic descriptions, slider position values, and interaction alerts (Fig. 2). Collectively, the result is a system of descriptions that provide an always available and up-to-date summary of the current state of the sim, along with a series of dynamic position values and interaction alerts that engage and inform the learner of important changes during their interaction. Static and dynamic descriptions (see Fig. 2, columns 1 and 2) provide an always available and always up-to-date description of the current state of the sim, for example, describing charges on John's body only when charges are present. As learners interact with John's leg or arm, they are provided with dynamic position values (Fig. 2 column 2) and interaction alerts (Fig. 2 column 3). With John's leg, position values indicate two regions, when "Foot rubbing on rug" and when "Foot off rug," with additional landmark descriptions indicating the slider start and end positions. As charges transfer to John's body, alerts regularly indicate accumulation of charge, e.g., "Electrons on body: 3." For the arm, twelve region descriptions describe distance from doorknob and nine landmarks describe the direction the hand is pointing, e.g., "straight up." A change in direction is indicated with an alert of "toward" or "away from" doorknob. Upon discharge, an alert indicates discharge occurred, amount of electrons discharged, and current position of arm. For the full description design, see "John Travoltage: A11y Design."

Evaluation of a Multimodal Design

We utilized iterative rounds of think-aloud interviews with learners with disabilities (learners with visual impairments N = 13 (Moore et al.)), learners with intellectual and developmental disabilities (I/DD) (N = 12) (Tomlinson et al., "Supporting Simulation Use") and without disabilities (N = 15) from primary school age to adult, to inform design of all sim features. We also included feedback from teachers, content experts, and expert screen reader users. Our most significant challenges and solutions are summarized in the next section. To evaluate later design stages, we conducted semi-structured interviews of adult learners with visual impairments (N = 6), and with children (N = 3) and college students (N = 3) without visual impairments.

Significant Design Challenges and Solutions

Through the iterative design work we encountered and addressed numerous design challenges. The following challenges and solutions were selected as being some of the most significant and generalizable.

Multimodal Challenge 1

A leg and arm are not typical interactive elements or UI components. How can we best scaffold productive interactions with the leg and arm across modalities?

- **Alternative Input Solution:** Leg and arm were implemented using a native HTML role (i.e., slider), allowing leg and arm swinging with intuitive arrow key interactions.
- **Visual Display Solution:** Green dashed-line boxes around leg and arm hint that items are moveable (a common approach used in PhET sims). These visual 'hints' disappear after first successful interaction. When using alternative input (e.g., the keyboard), the bright pink focus highlight indicates when leg or arm has focus.
- **Description Solution:** Leg and arm sliders were given action-oriented labels (i.e., "Leg swing" and "Hand position") to scaffold description users.
- **Sound Solution:** Auditory icons provide additional cues (rubbing or ratchet sound) and confirmation of successful interaction.

Multimodal Challenge #2

How can the sim ensure learners maintain a sense of how many charges are on John's body, even if they are not visually accessing the sim?

- **Description Solution:** Provided accurate real-time counts of electrons on body in two ways (see Fig. 2): 1) Interaction with leg gives interaction alerts to the user about charge accumulation (e.g., "Electrons on body: 5."); 2) Reading through dynamic scene gives an up-to-date description including charge information (e.g., "John has 5 charges on his body.")
- **Sound Solution:** "Charges on body" sound changes dynamically based on number of electrons, providing a qualitative sense of the amount of charges.

Description Only Challenge

How can the leg and arm positions be described in an engaging way that emphasizes key regions (rubbing on rug; at doorknob), while minimizing repetition, and verbosity?

- **Description Solution:** Reduced total number of position values to 15 for leg (positions -7 to 7), and 31 for arm (positions -15 to 15). Created description regions: 2 regions for leg "Foot rubbing on rug" or "Foot off rug;" 12 regions for arm describing distance to doorknob. Having positive and negative position values, with a central zero point, helped emphasize key regions, e.g., for the arm center position 0 is "At doorknob." Landmark descriptions added to some region descriptions provided additional orienting information and ensured region descriptions were not repetitive, i.e., 9 landmarks for arm movement, e.g., "hand pointing straight up," "pointing away from door," "last stop," etc.). Finally, dynamic directional changes (i.e., "Toward doorknob," "Away from doorknob") replaced regions and landmarks on direction changes, further reducing repetition and providing engaging feedback.

Sound Only Challenge

How can the "Charges on body" sound convey the amount of charges on John's body continuously, without overwhelming or distracting learners from other sim features.

- **Sound Solution**: Early designs of the "charges on body" sound includes sounds of objects bumping into each other (a metallic variation, and a glassy variation). These were consistent with the visual display of charges, but were found to be less pleasant for extended durations and lacked contextual relevance for visually impaired learners. Later designs included more 'electricity'-like sounds, settling on a low hum - reminiscent of the sound heard near an electric power station.

Semi-structured Interviews

Interviews began with 10 minutes of free exploration of the sim. Participants then answered a series of open-ended questions about their experiences and interpretation of: sim navigation, description or visual display, and sound. Last, participants completed three surveys ("John Travoltage Survey Questions"): A subset of questions from the BUZZ (Tomlinson et al., "BUZZ") audio user experience scale eliciting feedback on sound aesthetics; a 4-question usability scale, UMUX, eliciting feedback on the overall sim experience (Finstad); and a demographics and technology use survey.

Results

During free exploration, all learners explored the sim fully and described relationships between amount of charge and arm/hand location. All learners successfully interacted with the sim (Table 2) and most successfully interpreted all of the sim's representations (Table 3). Survey and qualitative highlights are presented below.

Table 2. Learner Interactions

Successful Open Play interactions	**Children (N = 3)**	**College students (N = 3)**	**Adult learners with VI (N = 6)**
Moved arm and leg	3/3	3/3	6/6
Transferred charges	3/3	3/3	6/6
Created discharge events	3/3	3/3	6/6
Explored relationship between charge amounts and arm position	3/3	3/3	6/6

Table 3: Learner Interpretations

Successful interpretation of sim features	**Children (N = 3)**	**College students (N = 3)**	**Adult learners with VI (N = 6)**
Scene description	-	-	6/6
Alerts	-	-	6/6
Carpet rubbing sounds	3/3	3/3	6/6
Charges on body sound	3/3	2/3	5/6
Arm movement (ratchet) sounds	2/3	3/3	6/6
Charge transfer sounds	3/3	2/3	6/6
Discharge sounds	3/3	3/3	6/6
Visuals for charge transfer	3/3	3/3	-
Visuals for discharge events(s)	3/3	3/3	-

Experience: Description + Sound Effects/Sonifications

Six adult screen reader users with visual impairments (self-described: low-vision (2) or blind (4)) used the sim with a screen reader and no visual display available. Participants rated the aesthetics of the sim (BUZZ scale) as a 25.7 (SD = 2.1) out of 28. They also rated the overall usability of the sim (UMUX scale) as 18.7 (SD = 5.4) 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 (5/6) commented positively on description clarity.

Experience: 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 sim experience more “immersive,” “interesting,” and “fun,” while one child (13-year old) expressed that the sounds were useful, because “having it be silent would just be kind of weird.” All learners 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 (college student) described the same sound as a “cranking” sound. Both learners indicated the sound was present to provide feedback on arm location changes.

Discussion

All twelve participants used the same sim, though they accessed different combinations of modalities during use. All were able to effectively use the sim and explored the key relationships. 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. Learners with visual impairments rated the aesthetics higher than, and usability lower than, learners without visual impairments. Learners with and without visual impairments may be using the auditory information in different ways with different expectations. Notably, learners with visual impairments were all new to using interactive simulations or anything similar while the learners without visual impairments had all used similar learning resources previously.

Insights from Diverse Learner Groups

Reflecting on the design process, we encountered many challenges while creating the multimodal sim. Some challenges were specific to each modality: we worked to refine the interactions, visuals, and descriptions to scaffold learner exploration of key concepts. Other challenges arose from the intersection of two or more modalities, such as designing sound effects/sonifications to layer and complement visuals and description simultaneously. Interviews and observations of sim usage throughout the design process with diverse groups of learners helped identify potential design challenges and insights, which may not have been found in a smaller, homogeneous sample size. Below are a few of the findings and potential benefits we have observed across learner populations.

Description

To date, during the design process descriptions have only been provided to learners with visual impairments. From work with other learners, we believe that many learners could benefit from hearing components of the description. In future work, we will explore the addition of new auditory display modes, including “short description” - which would provide access to some alerts, such as object names, displayed using Web Speech through the browser.

Sound

Some published sims have two sound modes, the default mode that plays the set of sounds available by default on sim load and an Enhanced mode that plays the default sound set plus additional sounds. The default sounds mode for John Travoltage includes the set of sounds listed in Table 1 - except for the charge transfer sounds. With the Enhanced sound mode enabled, users hear the full set of sounds listed in Table 1. Note: for all interviews, the Enhanced sound set was used. Across populations, almost all sounds were appreciated and used by all user groups. For example, we originally designed the ‘charges on body’ sound to help convey when charges were on John’s body, to support learners with visual impairments. Through interviews, we found that all learners were making use of and enjoying the ‘charges on body’ sound - so this sound was included in the set of sounds enabled by default. Feedback from physics teachers regarding the ‘charge transfer’ sounds indicated concern that it may make the visual electron charge representations sound “too physical”, so we included that sound in the Enhanced mode only.

Visual

John Travoltage was first published as a Java sim in 2006, redesigned and published in HTML5 in 2013 (increasing platform and device compatibility), and published with alternative input, description, and additional sound in 2018. For this most recent work on the sim, visual changes included addition of the keyboard help button and dialog, and moving of the sound button from inside the ‘scene’ down to the bottom navigation bar. In other sims, as we designed and implemented multimodal features, we have made changes to the visual display to improve the aesthetics, pedagogical scaffolding for all learners, and to increase alignment across the multimodal features.

Interaction

In past interviews with other sims, we have observed young children using the mouse or trackpad without bending their wrist - resulting in the learner moving their entire arm as they navigate the sim. In interviews with John Travoltage, we found some learners interested in switching between use of a trackpad and use of alternative input (specifically, keyboard input). For the youngest children we interviewed, use of the keyboard resulted in improved hand/arm positioning and possibly more deliberate exploration of some sim features. Switching to keyboard input could be more comfortable, and could provide more fine control during exploration for these students.

Conclusions

We present a multimodal science simulation with visual display and robust auditory display (description, sound effects, and sonifications) to support learners with and without visual impairments. Building on our prior work in developing navigation and description for complex interactives, we introduced the design of a multimodal physics sim and its evaluation with learners utilizing different combinations of modalities. This work contributes to continued advancement of inclusive design practices and research methods for developing and evaluating accessible learning resources.

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