Auditory Display in Interactive Science Simulations: Description and Sonification Support Interaction and Enhance Opportunities for Learning

Brianna J. Tomlinson
Georgia Tech
Atlanta, GA, USA
btomlin@gatech.edu

Bruce N. Walker
Georgia Tech
Atlanta, GA, USA
bruce.walker@psych.gatech.edu

Emily B. Moore
Univ. of Colorado Boulder
Boulder, CO, USA
emily.moore@colorado.edu

ABSTRACT

Science simulations are widely used in classrooms to support inquiry-based learning of complex science concepts. These tools typically rely on interactive visual displays to convey relationships. Auditory displays, including verbal description and sonification (non-speech audio), combined with alternative input capabilities, may provide an enhanced experience for learners, particularly learners with visual impairment. We completed semi-structured interviews and usability testing with eight adult learners with visual impairment for two audio-enhanced simulations. We analyzed trends and edge cases in participants' interaction patterns, interpretations, and preferences. Findings include common interaction patterns across simulation use, increased efficiency with second use, and the complementary role that description and sonification play in supporting learning opportunities. We discuss how these control and display layers work to encourage exploration and engagement with science simulations. We conclude with general and specific design takeaways to support the implementation of auditory displays for accessible simulations.

CCS Concepts

•**Human-centered computing** → *Empirical studies in accessibility;* Usability testing; Auditory feedback;

Author Keywords

Multimodal; interactive simulation; learning; visual impairment

INTRODUCTION

Science simulations are common and effective educational resources used to engage learners in exploration and inquiry [6]. They support exploration of physical phenomena in ways not possible in traditional lab experiences [1, 7]. These tools contribute to increased comprehension and positive learning experiences [1, 15]. However, simulations rely on visual representations as their primary modality for interaction and feedback. This makes them difficult for learners with visual impairment to use. Supporting access to simulations would make them inclusive to these learners who are otherwise largely left out of advances in STEM education [2, 45, 20].

This paper addresses simulation inaccessibility through the systematic design and evaluation for a pair of simulations that are highly representative of a wide range of learning interactives. The vast majority of widely-used interactives for classroom and homework use in primary and secondary education have a similar complexity, with 2-3 primary variables changing through 2-3 controls. Therefore, the results from this study can be applied to the design of non-visual representation methods for many interactive simulation.

CHI'20, April 25–30, 2020, Honolulu, HI, USA

ISBN 978-1-4503-6708-0/20/04. . . $15.00

DOI: https://doi.org/10.1145/3313831.3376886

RELATED WORK

Accessible Simulations

Levy and Lahav created the first sound-enhanced science simulations specifically addressing needs for students with visual impairment [20]. Prior research has shown how sound-enhanced learning environments are capable of providing comparable access and conceptual learning for students with visual impairment [19, 20].

Though the use of multimodal display amongst the producers of interactive simulations is increasing slowly, the majority of both existing and new interactive simulations remain inaccessible to many students with disabilities [21]. The PhET Interactive Simulations project has led a large accessibility initiative to implement auditory display and alternative input features within their free simulations. Advancements through this work include the development of design approaches and infrastructure for alternative input [36], description [37], and sonification [29] for a subset of PhET simulations.

Currently, integrating accessibility features into learning resources requires sophisticated implementation of multimodal technologies and context-specific design as well as significant development efforts [20, 25, 40, 48], which is a resource-intensive process. In this work we investigated the use of two physics simulations enhanced with auditory display features by eight adults with visual impairments. These simulations represent a common user interface and visual display scenario for interactive simulations, which emphasizes interaction through multiple sliders (also known in HTML as input type="range") with corresponding dynamic visual representations.

The two simulations presented here are relatively minimal in available interactions (through 2-3 sliders) but contain multiple on-screen representations (mathematical, physical, numerical, and uniquely size-scaled representations). They are pedagogically complex in the exploration and discovery of patterns (for the mathematical and physical representations). Even within visual-only representations, this is challenging from the learner's perspective [33]. Investigating these interfaces lays necessary groundwork for advancing more complex interactives.

Auditory Displays

The two simulations investigated were enhanced with auditory displays, including: 1) Description (speech displayed using screen reader software), and 2) Sonification (non-speech sounds displayed with Web Audio). These auditory displays convey real-time, important conceptual and contextual information about the simulation. Prior work found description and sonification successful in supporting access for learners with vision impairment. This work pursued a systematic evaluation of two simulations with related topics, similar user interface controls, and varying levels of complexity – which has not been previously explored.

Description

Screen-reader spoken natural language descriptions (which we refer to simply as 'descriptions') can provide access to live, recorded, or digital experiences, with the most robust existing guidelines and technical infrastructure developed for television [22], video [28], theatre [41], and static images [47]. Description for digital interactive resources present unique challenges, with best practices emerging across graphs [26], charts [24], interactive chemical structural formulas [38], and interactive scientific graphics [13, 16]. Collectively, these resources provide guidance on developing effective descriptions (e.g., regarding brevity, context, and timeliness).

The PhET project has expanded upon prior work in description, resulting in a description design framework for creating a system of descriptions for fully described interactive simulations. The Description Design Framework [35, 37] includes:
State Descriptions: State descriptions include both static and dynamic state descriptions, together representing the current state of the simulation, which are always up-to-date and available on-demand by the user at any time.
Responsive Descriptions: Responsive descriptions are triggered when an interactive object has focus — when navigated to or interacted with — and provide transient information (e.g., alerts) about the object's current state and other relevant changes occurring in the simulation.

Integration of descriptions which are timely, accurate, relevant, and support learning are key in supporting accessible educational experiences with simulations. Learners follow diverse sequences of interaction while using a simulation. The design of the simulation and any supporting materials seek to scaffold learners to follow productive pathways for learning, with many different pathways possible. Simulations present unique challenges in description design as they need to include introductory information to orient learners to the simulation and interaction pathways, in addition to informing the learner of relevant changes during interaction.

Sonification

Sonifications, non-speech auditory representations of information [17, 46], have a long history of use for presenting information in addition to or instead of visual displays [39, 46]. Sonifications can vary in complexity, and can leverage common human experiences or metaphors to support recognition, comprehension, and interpretation.

Parameter-mapped sonifications are often used to represent data directly [14]. For example, for a series of numerical data values, an associated tone increasing in pitch could convey an increase in the magnitude of the data values. If the data are continuous, the sound mapping could be continuous. If the data have multiple dimensions, multiple sound parameters could be changed (e.g., pitch and tempo), or multiple sounds could be displayed simultaneously [49].

Recent work has successfully used sonifications to represent relationships in interactive simulations, in order to give additional access modalities to diverse populations of learners [42, 43, 49]. Likewise, in their simulation-focused work with students with vision impairment, Levy and Lahav found that sonifications can support inquiry-based learning activities when used in scientific computer models [19, 20].

Description and Sonification

When used together, description and sonification give different layers of information (background, dynamic events, and alerts) through two different modalities: speech and non-speech audio. This use of different but related displays can reduce cognitive load and working memory [9, 34], engage the learner by invoking previous mental models and real-world representations of phenomena [11], and broaden access to the interactive learning materials for learners who require non-visual access [5, 18, 23]. Description conveys information about the simulation's representations and navigation, and keeps the learner updated regarding changes during interaction. Sonification can provide context, interaction cues, and auditory representations of objects and relationships that leverage our ability to discriminate sound sources [3, 27].

The body of work combining these two modalities is still small, and each context can be quite different (e.g., within pre-set curricula [18], or focused solely on accessibility [38, 21]). Thorough investigation of how to integrate description and sonification in representative situations (e.g., common user interface controls and number of variables) for flexible use by diverse learner groups will identify generalizable findings for other more complex contexts. To accomplish this, we investigate and seek to understand:

Q1) How do description and sonification impact interpretation and comprehension of interactive simulations?

Q2) How do description and sonification impact the usability and user experience of interactive simulations?

METHODS

We conducted a series of evaluations through semi-structured interviews and usability testing, including standardized user experience scales.

Participants

Ten adults with vision impairment participated in the study. Six participants were from local community organizations that provide outreach and training opportunities for people with vision impairment. Four participants responded to emails sent to mailing lists used by people with visual impairments. The analysis presented here contains data from eight of these interviews. Data from two of the interviews were excluded, due to technical issues that resulted in low quality screen and audio recordings. Though the number of participants is small (common in qualitative studies and studies involving users with low-incidence impairments), the in-depth interviews provided a rich data set for analysis, and we found the range of relevant participant experience reflects significant diversity across this user population.

The eight participants (6 female, 2 male) ranged in age from 24 - 59 (average age was 41). All participants had experience with PC and mobile screen readers, and reported using technology (e.g., phones, computers, and assistive tools) multiple times a day. Of the four participants who had familiarity with simulations or educational games, only one had used a PhET simulation previously. One of the two students had taken a science class in the last five years, but no other participants had recent STEM educational experience. Table 1 contains demographic information for each participant.

ID	*Vision Level*	*Familiar Screen Readers*	*Student*	*Sim Use*
P1	Low vision	JAWS, VO		Yes
P2	Low vision	JAWS		
P3	Blind	JAWS, NVDA, VO		
P4	Blind	JAWS, NVDA	Yes	Yes
P5	Low vision	JAWS, VO		Yes
P6	Blind	JAWS, VO		Yes
P7	Low vision	JAWS, NVDA, VO	Yes	
P8	Blind	JAWS, NVDA		

Table 1. Participant demographics

Simulations Used

We evaluated two HTML5 PhET simulations (or 'sims'): Ohm's Law [31] and Resistance in a Wire [32] (see references to links for published sims). Each sim was enhanced with description, sonification, and alternative input capabilities. Participants used a screen reader (NVDA) and a standard keyboard during sim use. These two sims are similar in their interaction design (e.g., sliders) and visual displays (i.e., mathematical, physical, numerical, and uniquely scaled representations) and both are used to convey physics concepts related to electrical circuits. Since they differ in the number of variables (complexity), they are good candidates for a structured evaluation of how description and sonification support interpretation and comprehension, and usability and user experience in accessible sims.

Ohm's Law

With Ohm's Law [31], learners increase and decrease two sliders to explore relationships between current (I), voltage (V), and resistance (R) in a circuit (Figure 1A). The Ohm's Law equation (V = I R) is displayed prominently. Below the equation is a circuit, consisting of a resistor connected to multiple batteries in series. A readout in the center of the circuit displays the value of the current in milliamps. To the right of the equation are two vertical sliders for voltage and resistance. Values for the voltage and resistance are displayed below the corresponding slider.

Changes in the sliders are reflected instantly in the equation, values, and the circuit displays. As the voltage or resistance is changed, letter size in the equation changes. For example, increasing the voltage slider value results in a size increase for the letters V and I in the equation, representing their proportional relationship. Slider changes are reflected in the circuit, including changes to the number of batteries in series, or to the amount of impurities within the resistor. A primary goal of this sim is to scaffold learners to investigate how changes in voltage and resistance affect current in a circuit.

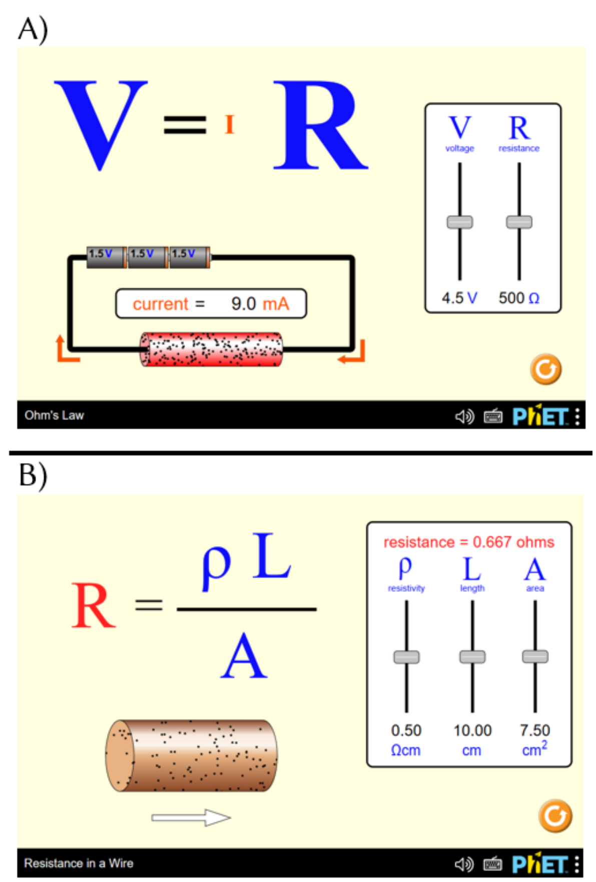

Figure 1. Screenshots of the PhET sims: A) Ohm's Law (top), and B) Resistance in a Wire (bottom). Images copyright PhET Interactive Simulations.

Resistance in a Wire

With Resistance in a Wire [32], learners increase and decrease three sliders to explore relationships between resistance (R), and the resistivity (ρ), length (L), and area (A) in a wire

(Figure 1B). The equation for resistance (R = ρ L / A) is displayed prominently. Below the equation is a wire with impurities in its material, represented by small black dots. To the right of the equation are three vertical sliders for resistivity, length, and area. The value for the resistance is displayed above the three sliders. The values for resistivity, length, and area are displayed below the corresponding slider.

Changes in the sliders are reflected instantly in the equation, values, and the wire displays. As the resistivity, length, or area are changed, letter size in the equation changes. For example, increasing the area slider value results in a size increase for the letter A in the equation, and a size decrease in the letter R, indicating their inverse relationship. Slider changes are reflected in the wire, such as changes to the resistivity (changes to the amount of impurities), length, or area. A primary goal of this sim is to scaffold learners to investigate how changes in resistivity, length, and area affect resistance in a wire.

Accessibility Features

Alternative Input

All interactive elements of the sim are accessible using alternative input. When using a keyboard, standard conventions for use of Tab and Shift+Tab can be used, as well as the typical screen reader shortcuts. Sliders can be adjusted using the Arrow keys, Pg Up/Down, Home, and End keys. In addition, Shift+Arrow keys can be used for adjusting sliders in smaller steps. A list of keyboard shortcuts are available through a menu option at the bottom of the sim.

Description

Description was designed using PhET's Description Design Framework [36] and consists of state descriptions and responsive descriptions. State descriptions include both static and dynamic state descriptions, that together describe the current state of the sim, and are always up-to-date, and available on-demand by the user at any time. In Figure 2, we show a subset of description from Ohm's Law to illustrate the structure used across both sims. In Figure 2, headings are indicated by "H1," "H2," and "H3," filled and numbered circles indicate interactive objects and their focus order, and unfilled circles indicate responsive descriptions triggered by interaction. The state descriptions (Figure 2, first and second columns) consist of a screen summary (brief summary of representations and interactive objects in the sim), Play Area (description of equation and physical circuit or wire, and sliders), Control Area (containing the Reset All button), and Sim Resources (containing keyboard shortcuts and PhET menu buttons). Responsive descriptions (Figure 2, third column) are triggered when an interactive object has focus - when navigated to or moved - and provide transient information (e.g., alerts) about the objects current state and other relevant changes occurring in the sim. Responsive descriptions include the reading out of current slider value on focus, and a brief comparison of the relative size of variables in the equation immediately upon slider value change.

Sonification

Sounds implemented in the sims are listed in Table 2. Previously completed formative evaluations were used to inform

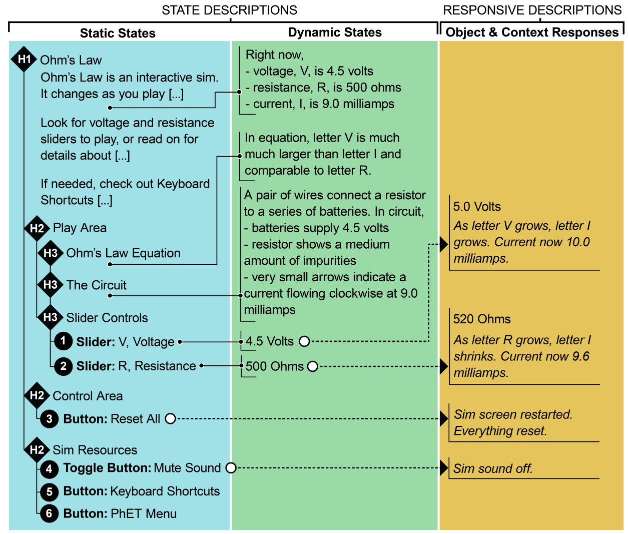

Figure 2. Description in the *Ohm's Law* Sim

Sim	*Slider Movement Sonification Description*
Ohm's Law	**"Current" Value:** Repeating short 2-second sound clip, playback rate (pitch change) and tempo increase and decrease
	Resistance and Voltage Slider Feedback: Synthesized tick, neutral Wood-block timbre
Resistance in a Wire	**Resistance Value:** Marimba timbre, pitch increases/decreases as value increases/decreases

Table 2. Sonification mappings for *Ohm's Law* and *Resistance in a Wire*.

the sound designs. In Ohm's Law, the most important information to convey is how the value of current changes as voltage or resistance is changed. Because of this, the sound design was structured so that the most salient sound during slider interaction represents the amount of current. As the sliders are changed, a repeating short 2-second sound clip is played reflecting the amount of current. This clip is repeated during interaction, at varying speeds, causing a fast tempo & high pitch (larger current value), or a slow tempo & low pitch (smaller current value). It fades in at the start of interaction and fades out once interaction stops. Playing the sound for a short duration, rather than playing it continuously, reduces listener fatigue and emphasizes the changing value.

In addition to the "current" sound, slider movements play a neutral-timbre tick (reminiscent of a wood block), indicating a change in slider value. This is a secondary information layer that can be used in addition to or instead of the responsive description. Another type of sound is available within all sound-enhanced PhET sim: a press of the Reset All button plays a short sound clip to indicate that the sim has been reset to its starting state.

In Resistance in a Wire, the most important information to convey is how the value of resistance changes as resistivity, length, or area are changed. The sound design was structured so that the most salient sound during slider interaction represents the amount of resistance. A discrete marimba strike, with pitch mapped to the amount of resistance, is played as the sliders are moved. A smaller resistance value is represented by a higher pitched marimba strike, and a larger resistance value is represented by a lower pitched strike.

Evaluation Materials

Semi-Structured Interviews

Semi-structured interview questions were used to probe each participant's interpretation and comprehension of the description, sonification, and their overall understanding of the sim-specific content (for Q1). A set of general questions were asked first (e.g., "Can you describe what's in the sim?"), to collect information without influencing learner word choice or content focus. General questions were followed by a set of more specific questions targeting learner interpretation of the physics relationships (e.g., "What is the relationship between V and I?"), descriptions ("Can you talk about the descriptions from the screen reader?"), sonifications ("Can you tell me what happens to the sounds when Length gets bigger?").

Next came a series of questions focused on the combined user experience of the description and sonification, and their overall likes/dislikes from the sim (e.g., "Is there anything you particularly liked about the sim? Disliked?") (Q2). Lastly, follow-up questions were asked at the interviewer's discretion. After the second sim use, participants were also asked to compare and contrast these two sims and their experience with both. If a participant answered any question while responding to an earlier one, that question was skipped later in the interview.

Usability and User Experience Evaluation

After the interview questions, participants responded to three standardized measures of usability and user experience as quantitative feedback in addition to their earlier qualitative comments: the Usability Metric for User Experience (UMUX) [10]; the BUZZ audio user experience scale [44]; and the System Usability Scale (SUS) [4]. Each participant responded to these questions for overall usability (including effectiveness, satisfaction, and efficiency) and audio user experience for the two sims. The scales support direct comparisons between the description and sonification for each sim, letting us explore differences between the number of controllable variables and representation complexities within each sim (Q2).

Procedures

At the beginning of the session, each participant completed the ethics committee approved consent procedures (a research consent form and recording permission). Each session was 1.5 hours in duration, and the participant's sim use was screen recorded. The order of sims was counterbalanced: five participants used Ohm's Law first, and three participants used Resistance in a Wire first. Each session consisted of:

1) Free Explore. During Free Explore, the participant explored one sim independently while "thinking aloud." Free Explore ended when participants told the researcher they were ready to move on to the next part of the session.

2) Semi-structured Interview Questions. A series of sim-specific questions were asked regarding their interpretation and comprehension, and their overall experience (summarized previously in "Semi-Structured Interviews"). Participants were encouraged to use the simulation while answering the questions.

3) Usability Evaluation. Participants completed the UMUX, BUZZ, and SUS scales for each sim to measure quantitative ratings for usability, audio user experience, and user experience, respectively. UMUX and SUS were answered based on their entire experience (interaction, description, and sonification). BUZZ was rated based on the overall audio user experience. We used these scales to compare the sims and sound designs, and to augment the qualitative data.

4) Demographics. Participants reported general and assistive technology usage, their previous experience with sims, educational games, and any recent science education. They only answered the demographics questions once.

During the session, the researcher took structured notes on participant interaction behavior and responses to all surveys. A complete list of interview questions and surveys are available at https://bit.ly/semi-structured-survey.

Four participants (P1, P2, P3, P5) continued on to complete part 1-3 for the second sim in the same session (i.e., they used both sims in the same session). The remaining participants returned for a second session consisting of parts 1-3 with the second sim (i.e., using one sim per session for two sessions). Interview session amount (1 or 2 sessions) and duration differed to ensure each participant had ample time for exploration, providing feedback, and qualitative reflection across sims, and to fit participant schedules. Participants were compensated $45 total at the end of the session(s).

ANALYSES

The data were analyzed through descriptive analysis, interaction behavior coding, and usability scale scoring. Screen recordings from the session were analyzed within the software Atlas.ti [12]. Screen recordings from each simulation use were divided into two sections: Free Explore and sim-specific questions, but only free explore was coded for interaction behaviors. Usability scales were scored based on their published scoring methods. A within-subjects design was used to compare the detailed information collected for each participant's experience using the two sims.

Comprehension and Interpretation

Interviews

The second section of the screen recording contained the user responses to the sim-specific semi-structured interview questions. This recording and the interviewer's notes were used to analyze participant comprehension and interpretation of the description, sonification, and their overall understanding of the sim-specific content. Responses to physics concept and description/sonification mapping questions were coded as correct or incorrect. Responses to all questions were coded for the presence or absence of explicit references to the physical representation (circuit or wire). Counts of codes for each question type (e.g., correct/incorrect) were tabulated.

Ohm's Law Sim

Question		*Correct Responses*
What's the relationship between...		
	V and I?	4
	R and I?	5
What changes when you move something?		5 accurately described circuit
What happens to the sound when you make V...		
	small?	7
	large?	7
What happens to the sound when you make R...		
	small?	7
	large?	7

Table 3. Accuracy for the comprehension and interpretation questions focused on description, sonification, and sim-specific concepts.

Resistance in a Wire Sim

Question		*Correct Responses*
What happens to R when...		
	ρ gets bigger?	4
	L gets bigger?	6
	A gets bigger?	6
What changes when you move something?		7 accurately described wire
What happens to the sound when you make length (L)...		
	small?	6
	large?	6
What happens to the sound when you make area (A)...		
	small?	7
	large?	7

Table 4. Accuracy for the comprehension and interpretation questions focused on description, sonification, and sim-specific concepts.

Usability and User Experience

Interaction Behaviors

Free Explore was coded for three behaviors: 1) accessing state descriptions, 2) interacting with the simulation sliders (resulting in access to responsive descriptions), and 3) any other behaviors. In coding, transitions from one behavior to an alternate behavior required a duration of at least 9 seconds or more of the alternate behavior. Periods of time when users were engaging in behaviors 1 and 2 were tabulated, and rounded to the nearest 15 second increment.

Usability Scales

Descriptive statistics were determined for responses to each scale (UMUX, BUZZ, and SUS) for individual factors and for the entire scale, based upon the published scales scoring. UMUX was scored out of 24, BUZZ's total score and asthetics sub-score were out of 77 and 28, respectively, and SUS was scored out of 100.

Interviews

Responses to questions regarding participants likes and dislikes were coded for presence and amount of positive or negative comments. Counts of codes for each question type (e.g., component or feature) were tabulated.

RESULTS

Comprehension and Interpretation

Interviews

During the semi-structured interview, participants were asked to respond to a series of questions to probe their understanding of the conceptual relationships conveyed in each sim, and their interpretation of the description and sonification (Q1). Results from a subset of questions related to comprehension of physics concepts and interpretation of sonification mappings conveyed in the sim are in Table 3 and 4. Note: for Ohm's Law, two participants (P1 and P3) were confused by the use of the variable "I" for "current," contributing to their incorrect responses regarding relationships between "I" and other variables.

When answering physics relationship and description questions for Resistance in a Wire, seven (all except P1) discussed the physical properties of the wire (conveyed through state descriptions only) in addition to the proportional or inverse mappings provided through the responsive descriptions.

With Ohm's Law, all participants stated their like of the "current" sound, and two participants thought it resembled electricity directly ("How would you describe the sounds?"; and "Do they remind you of anything?"). Four participants explicitly stated that the mappings for both current and the slider clicks were easy to understand.

Across sims, most correctly described the audio mappings but struggled to contextualize the relationship between the variable presented (e.g., resistivity) and resistance. During sim-specific questions, three (P3, P5, P6) said that they had less familiarity with the concepts within Resistance in a Wire compared to Ohm's Law. P5 explained that,

> The descriptions were ok, (but) I would definitely have to know, I would have to have some 'pre-something,' because some of these things [the topics] are not familiar to me.

Usability and User Experience

Simulation Interaction

Participants used the description and sonification during the Free Explore portion of the sessions for a range of 1 - 14 minutes; times varied based on the participant's depth of exploration of the sim. In Figure 3, each participant's Free Explore time is shown, indicating time spent: 1) navigating and listening to state descriptions (indicated by regions filled with diagonal parallel lines), 2) time spent interacting with the sim sliders and hearing the responsive descriptions and sonification (indicated by solid filled regions), and 3) pauses in behaviors 1 and 2 (indicated by a solid vertical line). Pauses ranged from 15 seconds to 7 minutes, and included behavior

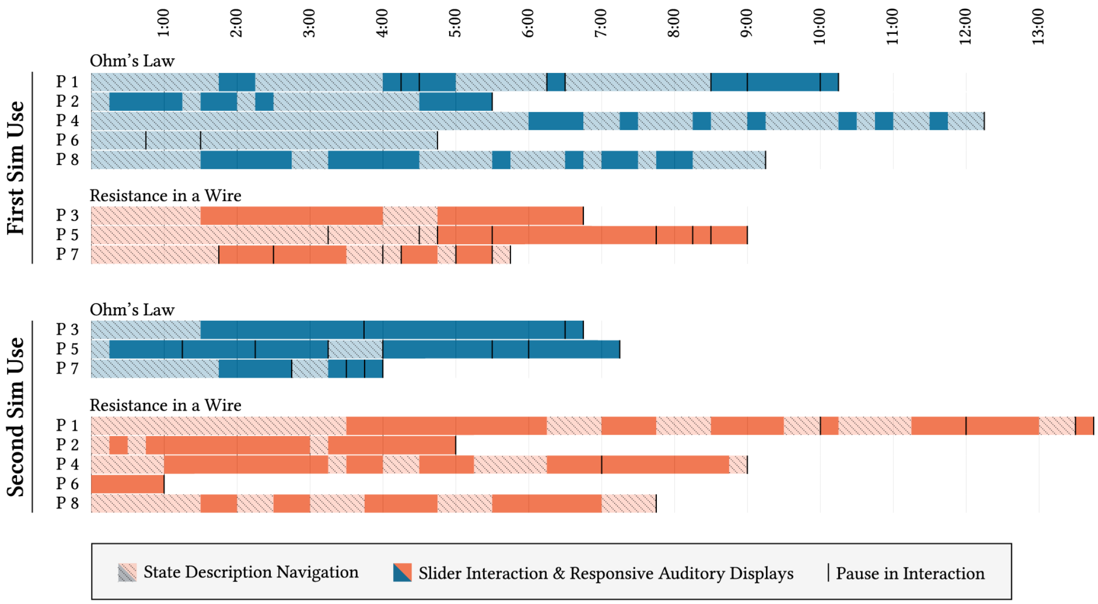

Figure 3. Interaction behaviors during Free Explore.

such as how pauses to "think aloud" and pauses to ask a question about the screen reader or to change screen reader settings (e.g., speech rate). Some participants (P1, P3, and P5) also spent time (1-3 minutes) investigating the PhET menu control, which is not relevant to the conceptual goals of the sims, and considered in Figure 4 as a pause in interaction.

Most participants (Ohm's Law: 8, Resistance in a Wire: 7) navigated through the state descriptions with the virtual cursor, either in detail (Ohm's Law: 6, Resistance in a Wire: 5) or skimming through (Ohm's Law: 2, Resistance in a Wire: 2). Seven participants then navigated to the sliders and began interacting: triggering responsive descriptions and sounds indicating changes to the slider value and representations in the sim. P4 was the most thorough in her reading of Ohm's Law's state descriptions, taking 6 minutes to read and "think aloud" through this information. P4 made over a dozen transitions between reading the state descriptions and moving sliders/listening to responsive descriptions and sounds. She spent less time with the state descriptions in subsequent passes.

Notably, participant P6 engaged in a less common interaction sequence. With his first sim, Ohm's Law, P6 read through only the state descriptions before moving on to the next segment of the interview (he did not hear any responsive descriptions or sounds). Later in that interview he interacted with the sliders, and heard the responsive descriptions and sounds. For his second sim, Resistance in a Wire, P6 engaged only through slider movement (and heard the responsive description and sonification). He showed comfort with relying solely on the responsive descriptions in his second sim use, supported by the similarity in overall structure between both sims. The adaptable, changing interaction behaviors demonstrated how participant's user experience changed within one sim and how they transferred usability knowledge between sims (Q2).

Usability and User Experience Scales

Overall sim usability (Q2) was measured by two usability scales: UMUS and SUS. Audio user experience (overall and aesthetics) was measured by BUZZ. Mean user responses shown are shown in Table 5. Both sims had similar usability and user experience scores. Overall participants thought the sims had good usability, and generally enjoyed the sound aesthetics.

Sim	UMUX (out of 24) Mean (SD)	BUZZ Aesthetics (out of 28)	BUZZ Total (out of 77)	SUS (out of 100)
Ohm's Law	20 (5)	23.8 (3.4)	67.7 (10.5)	82.1 (23.4)
Resistance in a Wire	18.4 (5.8)	23.3 (3.3)	66.1 (6.1)	82.1 (18.9)

Table 5. Usability and user experience scale scores.

Interviews

User experience questions (e.g., Table 6) asked the participant to reflect on the entirety of their sim usage and probed for preferences (Q2). For both sims, almost all reported enjoying the description and sonification. P6 enjoyed his experience, but wished the sounds for the current ("I") would play a little more, so he could notice the difference more easily: *"The sound needs to change, maybe like different tones. It's not really much of a difference."* In contrast, P4 explained, how much she enjoyed the description and sonification in both sims, but particularly so in Resistance in a Wire:

> I think the descriptions for them [both sims] are really good. And like I said, I liked the sounds because they were a lot shorter because there's more things to do.

Question: Is there anything you particularly liked/disliked about the sim?

	Description	Sonification
Ohm's Law	7 / 0	8 / 3
Resistance in a Wire	7 / 0	6 / 1

Table 6. Participant responses to semi-structured interview questions asking about their likes and dislikes.

After using both sims, participants were asked to compare and contrast their experiences. Reflecting on his experience after using both sims, P1 thought that using the first sim again (after interacting with both) would be easier. P4 compared the concepts within the sims, *"the first one [Ohm's Law] was a little bit simpler...the descriptions and stuff were the same on both, they were really good."* During interaction, she thought it was easier to imagine the changes to the physical object in Resistance in a Wire, compared to the abstract circuit in Ohm's Law:

> Because it was about something that was maybe tactile, that we've seen,...it's easier for me to be like 'I know what extremely thin looks like, I know what extremely long means.'

Participants, when asked "What's the difference between this simulation and the other one you used?" responded with three types of similarities and differences: description (4), sonification (6), and physics concepts (4). Regarding this, P8 stated:

> They were about equal. They keyboard keys that I used were the same, and it was basically the same method of doing things, with the tabs and the arrows, and the sliders. [For the sounds], they pretty much did the same thing. They increased and decreased the pitch depending on what variable was being changed, well, depending on what change was being made to a variable. I found it very easy.

At the end of the sim-specific questions, we asked, "Do you think it [the sim] would be useful for helping someone with vision impairment learn [about Ohm's Law/Resistance in a Wire]?" Participants agreed that the sims successfully present the concepts and methods to explore them (Ohm's Law: 7; Resistance in a Wire: 8). P6 disagreed with this statement, when talking about Ohm's Law. He believed a more pronounced pitch/tempo mapping for the current value would make it easier to understand, and found the mapping for the resistance value easier to interpret for that same reason. All other participants thought these sims would be useful. For example, P8 stated,

> You can't obviously change the length and the area of a wire for real, but this kinda lets you so you can actually know how the different variables will change.

P5 strongly agrees with this sentiment, *"I really think it could be useful. Absolutely."*

DISCUSSION

As interactive simulations are developed to support learners, it is key to understand how to build them to be accessible for a diverse population of users. One way to accomplish this accessibility for learners with visual impairment is to include description and sonification modalities within the simulations. Based on our evaluation of two PhET sims with similar user interface controls and representations, but differing levels of complexity, we showed that description and sonification can support learner interpretation and comprehension. In addition, these components added to the usability and user experience.

Comprehension and Interpretation

In our work, we evaluated how the description and sonification supported learner comprehension and interpretation. To build similarly effective interactive simulations, we recommend the following approaches.

1: Use Varying Layers of Feedback

When exploring the various layers of description and sonification, participants interpreted the content and relationships accurately. This is because we could provide context, instructions, and feedback resulting from user-driven interaction. We used a combination of static state, dynamic state, and responsive descriptions which varied in length. We also used a combination of sonifications to inform the user about changes to the most important concept or relationships. Additionally, these sonifications reinforced feedback for the user's interactions.

1A: Use Multiple Auditory Representation Types.
Description and sonification can provide complimentary information, supporting interpretation of the sim's content. Description is useful for orienting the user, identifying objects, conveying terminology, and for providing semantic meaning, while sonification is useful for rapid feedback and cueing of key relational information. When asked about the science content, participants explicitly discussed different aspects of the descriptive representations (e.g., the equation size, changes to the circuit or wire, etc.). Similarly, when asked about their interpretation of the sonifications (e.g., changes to "current"), they spoke in detail about the sound layers. Notably, participant responses included a variety of details presented through both types of auditory representations. This demonstrated how they relied on both types of auditory representations to interpret the sim content, similar to how users rely on multiple representations within the visual-only versions.
Recommendation: Use multiple auditory representations, particularly when there are multiple visual representations for the content.
Example: Resistance in a Wire consists of three main visual representations: an equation (where size changes reflect the variable relationships), a physical representation (where the wire changes to reflect the values of the sliders), and numerical readout/sliders (where the number and slider height emphasize the values of the controllable variables). Using lengthy description for each could overwhelm and confuse the learner. Our use of carefully crafted description coupled with sonification that emphasized the most important relationship was considered effective by our participants.

1B: Use Organized, Modular Auditory Representations.
State descriptions are provided through a well-organized, hierarchical structure, supporting ease of navigation and interpretation. Responsive descriptions and sonifications are designed

to be complimentary; both support rapid conveyance of information needed as changes are made in the sim. During use of these modular sets of information, we observed changes in participant interaction patterns over time. Initially users typically relied more on the state descriptions, and over time relied more on the responsive description and sonification. Some even reduced their overall responsive description use and focused on interpreting the sonifications.
Recommendation: Creating highly-organized and modular auditory representations supports a variety of use patterns, and allows for engaging with content in different ways - including in detail, skimming, and selectively focusing on individual representations.
Example: State descriptions in Resistance in a Wire give a brief introduction to the sim, a hint to start interacting, and detailed descriptions about the representations within the play areas and control area. Participants can choose to explore each of these in detail, or begin interaction with the sim immediately. Participants can listen to the full responsive descriptions as they change the sliders, or can continue interacting, 'interrupting' a prior responsive description with a new one. For example, they could hear "5 Volts" when changing the value of a slider, and then move the slider again, and hear the next value, without listening to the full responsive description. They could also choose to focus on the sonifications with more continuous interaction (thus, more 'interruption' of the responsive descriptions): short clicks provide direct feedback on slider movement, and the sonification for the main value update to reflect the trend of the change.

2: Provide Immediate Feedback and Consider Extremes
As users interact, they are provided with immediate sonification and description information. Importantly, this information changes in (what becomes, through use) predictable ways. At extreme sim scenarios, the sonification and description also provided indications of an extreme scenario. We aimed to ensure users could quickly understand the changing relationships through sound and/or description. During the sonification-specific interview questions, often participants would go back quickly through the sim to validate their interpretation of the relationship before describing it. They could quickly confirm their previous understanding before answering the question (or correct it; e.g., P4, P6), and showed ease in doing so.
Recommendation: Use short description and sonification to update the user of the sim changes as they complete their interaction. If needed, emphasize the edge cases to highlight the sonification mapping or the changes in responsive descriptions.
Example: For Ohm's Law, at the highest Voltage (9.0V) and lowest Resistance (10 Ω), there is a noticeably fast tempo, high pitched trill representing the maximum current, and the equation is described as "In equation, letter V is much much smaller than letter I, and much much larger than letter R." Users can jump between the bottom and top slider values (using Home and End keys) to compare these contrasting cases rapidly reflected in both the sonification and description. Alternately, holding down an arrow key results in the slider moving through all available positions, playing the updated tones as it moves through each current value in turn.

Usability and User Experience
Specific usability principles are known for visual displays; however, they have not been explicitly tested within interactive simulations that rely on non-visual modalities. This work provides evidence and support for the continued inclusion of these principles for description and sonification. Q2 focused our evaluation on these concepts.

3: Be Consistent Across Sims
Participants reported similar usability and user experience scores for both sims. They also adapted their interaction behavior for the second sim (e.g., usually spent less time in the state descriptions and more time interacting with the sliders/observing the responsive descriptions). For these sims, we were consistent in the implementation of similar user interface controls and their feedback, description structure, and sonifications, since they had similar interaction, visual displays, and related concepts. For instance, these two sims were navigated using the same alternative input keys, and state and responsive descriptions were structured similarly. Attributes of the sonification were different (e.g., a looping sound vs. a single tone for reach current/resistance value), but both still had usability similarities, including a pitch-mapped sonification and the same user interface control sounds.

3A: Be Consistent Across User Interface Controls.
In their first sim use, some participants spent a significant amount of time investigating the PhET menu control; in their second sim usage, as participants already knew the menu, they avoided it (P1, P3, P5). Participants in general spent more time using the sliders earlier in the Free Explore for the second sim.
Recommendation: Use similar description, behavior, and sonification across simulations for the same (or generally similar) user interface components.
Example: Both sims supported the Home and End keys for jumping between extremes on the sliders, and used the Arrow or Shift+Arrow keys to change slider values.

3B: Be Consistent in Description Structure.
In addition to similar user interface controls, we used a similar description structure across the sims. Participants generally spent less time exploring the state descriptions (particularly the static ones) in their second sim usage. They had high accuracy describing the relationship between the variables within the sim (e.g., for the physical and equation representations).
Recommendation: Use a consistent structure and level of detail for the different sections of description (static state, dynamic state, and responsive descriptions).
Example: Both sims followed a similar description structure (see Figure 2) for the static descriptions: a brief summary of the sim, interaction hint, and then a detailed description of the play area, control area, and sim resources. The responsive description alerts also followed a similar parallel structure: first providing the new slider value, then the most relevant change in the sim, and then the overall main variable value (e.g., "5 Volts. As letter V grows, letter I grows. Current now 10 milliamps").

3C: Be Consistent Across Sonifications.
We also used a similar sonification structure across the sims.

Participants reported similar audio user experience scores across sims, and they had high accuracy describing the sonification mappings and their relationship to the sim content.
Recommendation: Use similar sonification for common user interface controls, and consistently sonify the most important concept or relationship with the most salient mapping.
Example: Slider interaction across sims was represented through short looping, or single-tone feedback. The main concept (i.e., Current, or Resistance) was mapped to a changing pitch, a very salient change for sound design.

4: Support Error Recovery and Rapid Reset
Resetting the sim state (user interface controls, description, and sonification) allowed the users to restart exploration if they become confused about their place in the sim or the relationship they were observing. Half of the participants used the reset button, and during the interview at least one (P7) reported it as a feature they really liked in the sims.
Recommendation: Include a fast reset functionality to let users start over if they want to return to the initial state or get confused.
Example: Both sims had a reset button which was listed in the control area section of the state descriptions. When 'tabbing' through the sim, it was located just after the sliders, so users could quickly navigate to it.

5: Support the Ability to Repeat an Exploration Pattern
In addition to resetting the sim, we aimed to support the ability to intuitively and quickly repeat or "redo" an experiment/change. This replicability is important to a learner's pattern-finding (no matter the modality), and is important in developing mechanistic reasoning for the sim's behavior. Participants often repeated exploration patterns to understand the underlying concepts represented in the sim, or to gain more evidence for their ideas about the mappings. Short total time from first exposure to repeated exploration patterns, particularly for those with no previous experience supports how that replicability contributed to comfortable interaction.
Recommendation: Support easy repetition of an interaction pattern, and consistent feedback for the same action.
Example: In either sim, moving the slider always resulted in sonifications (i.e., slider feedback and the main value). Slider movement also resulted in a three-part description (e.g., "5 Volts. As letter V grows, letter I grows. Current now 10 milliamps."). Participants could move the slider up once to hear the changes. Then they could quickly move it down and back up to hear the same information *again* allowing them to confirm or refine their understanding of what occurred.

FUTURE RESEARCH AND LIMITATIONS
While our study addressed the accessibility of slider controls and multiple representations of relationships within a pair of interactive science simulations, further systematic exploration could include interactives with freely movable objects (2-dimensional drag-and-drop objects), comparisons with other simple interactions (1-dimensional movement), and more dynamic scenarios where not all changes in the sim are directly user controlled (for example, where randomness of a model parameter is central to the concept to be conveyed, e.g., the PhET sim *Molecules and Light* [30]). The five design takeaways can serve as a basis for investigating these more complex designs, utilizing knowledge found from prior explorations. Some of the takeaways (e.g., 3) are well-known principles, but are rarely tested, discussed, or used for specialized applications (and rarely in general ones, [8]). Future studies should expand our usability-focused takeaways through larger, in-depth evaluations for each individual usability principle. This would cover the full range of functionality and modifications to the designs to support accessibility through description and sonification.

Small sample size is a common difficulty within these studies (even more so here with the exclusion of two participants' data); however, even small-scale studies can make valuable contributions to this research area, particularly when utilizing a rich data set. Future work should build from this and try to discover whether or not these trends hold across larger user populations.

In this work, the disciplinary vocabulary is introduced in the state description (e.g., how "I" represents "current" or "ρ (rho)" represents "resistivity"). This information was not recalled by some participants during the session. If deployed within a science class, students would likely have some experience with content-specific terminology before their sim exploration, or developing knowledge of this terminology could be a goal of sim use. The presence of teachers and peers, and/or additional supporting information (e.g., activity prompts) could alleviate some issues with terminology. Future work should also study how description and sonification-enhanced simulations impact learners in authentic classroom environments.

CONCLUSION
We completed a unique evaluation of two interactive simulations with learners with vision impairment; identified important design recommendations for supporting comprehension among a diverse group of learners (e.g., science knowledge, screen reader experience); and emphasized opportunities for applying common HCI heuristics and principles to this context (inclusive educational tools). This work provides an example for how and why these basic concepts should be integrated into multimodal simulations. These guidelines can be applied to other inquiry-based learning interactives, particularly to support those who utilize non-visual representations for access.

ACKNOWLEDGEMENTS
We thank John Blanco and Taliesin L. Smith (PhET Interactive Simulations) for their significant contributions to the design and implementation of auditory display in PhET sims. We thank Prakriti Kaini and Siyan Zhou (Georgia Tech) for their help with data collection. This material is based on work supported by the National Science Foundation under DRL-1621363.

REFERENCES
[1] Sasha A. Barab, Kenneth E. Hay, Michael Barnett, and Thomas Keating. 2000. Virtual solar system project: Building understanding through model building. *Journal of research in science teaching* 37, 7 (2000), 719–756.

[2] Bernhard Beck-Winchatz and Mark A. Riccobono. 2008. Advancing participation of blind students in Science,

Technology, Engineering, and Math. *Advances in Space Research* 42, 11 (2008), 1855–1858. DOI: http://dx.doi.org/10.1016/j.asr.2007.05.080

[3] Albert S. Bregman. 1990. *Auditory Scene Analysis: The Perceptual Organization of Sound*. MIT Press.

[4] John Brooke. 1996. SUS-A quick and dirty usability scale. In *Usability Evaluation in Industry*, Bruce; Weerdmeester Bernard A.; McClelland Ian L. Jordan, Patrick W.; Thomas (Ed.). Taylor & Francis, Chapter 21, 189–194.

[5] Lorna M. Brown and Stephen A. Brewster. 2003. Drawing by Ear: Interpreting Sonified Line Graphs. In *Proceedings of the 2003 International Conference on Auditory Display*. 152–156. DOI: http://dx.doi.org/10.1.1.597.8532

[6] Cynthia D'Angelo, Daisy Rutstein, Christopher Harris, Geneva Haertel, Robert Bernard, and Evgueni Borokhovski. 2014. *Simulations for STEM Learning: Systematic Review and Meta-Analysis Report Overview*. Technical Report. https://pdfs.semanticscholar.org/6bf2/15af93f56403e2fe8cb8affe798d65b1142d.pdf

[7] Chris Dede. 2000. Emerging Influences of Information Technology on School Curriculum. *Journal of Curriculum Studies* 32, 2 (2000), 281–303. https://pdfs.semanticscholar.org/6cbb/14465e73fe55968713d78b34106d8f084a3a.pdf

[8] Nicoletta Di Blas, Paolo Paolini, and Marco Speroni. 2004. "Usable accessibility" to the Web for blind users. In *Proceedings of 8th ERCIM Workshop: User Interfaces for All*.

[9] M. Dubois and I. Vial. 2001. Multimedia design: the effects of relating multimodal information. *Journal of Computer Assisted Learning* 16, 2 (2001), 157–165. DOI: http://dx.doi.org/10.1046/j.1365-2729.2000.00127.x

[10] Kraig Finstad. 2010. The usability metric for user experience. *Interacting with Computers* 22, 5 (2010), 323–327.

[11] William W. Gaver. 1986. Auditory Icons: Using Sound in Computer Interfaces. *Human-Computer Interaction* 2 (1986), 167–177.

[12] Scientific Software Development GmbH. 2019. Atlas.ti. (2019). https://atlasti.com/

[13] Bryan Gould, Trisha O'Connell, and Geoff Freed. 2008. Effective Practices for Description of Science Content within Digital Talking Books. (2008). http://ncamftp.wgbh.org/ncam-old-site/experience_learn/educational_media/stemdx.html

[14] Florian Grond and Jonathan Berger. 2011. Parameter Mapping Sonification. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G. Neuhoff (Eds.). Vol. 15. Logos Publishing House, 363–397. http://sonification.de/handbookhttp://www.logos-verlag.comhttp://sonification.de/handbook/chapters/chapter15

[15] Jos J.A. van Berkum and Ton de Jong. 1991. Instructional environments for simulations. *Education and Computing* 6, 3-4 (1991), 305–358. DOI: http://dx.doi.org/10.1016/0167-9287(91)80006-J

[16] Kyle Keane and Christina Laverentz. 2014. *Interactive Scientific Graphics*. Technical Report. Wolfram Research, Inc., Champaign, IL. 1–50 pages. http://diagramcenter.org/wp-content/uploads/2014/06/Interactive_Scientific_Graphics_Submission23june2014.docx

[17] Gregory Kramer. 1994. Preface. In *Auditory Display: Sonification, Audification, and Auditory Interfaces*. xxii – xxviii.

[18] Orly Lahav, Jihad Kittany, Sharona Tai Levy, and Miriam Furst. 2016. Perception of multi-varied sound patterns of sonified representations of complex systems by people who are blind. *Recent advances on using virtual reality technologies for rehabilitation.* 9, 2 (2016), 139–145.

[19] Sharona T. Levy and Orly Lahav. 2012. Enabling people who are blind to experience science inquiry learning through sound-based mediation. *Journal of Computer Assisted Learning* 28, 6 (2012), 499–513. DOI: http://dx.doi.org/10.1111/j.1365-2729.2011.00457.x

[20] Sharona T. Levy, R. Peleg, Orly Lahav, N. Chagav, and V. Talis. 2016. Listening versus Looking: Learning about Dynamic Complex Systems in Science among Blind and Sighted Students. In *Annual International National Association for Research in Science Teaching (NARST)*. Baltimore, MD.

[21] Gi Zen Liu, No Wei Wu, and Yi Wen Chen. 2013. Identifying emerging trends for implementing learning technology in special education: A state-of-the-art review of selected articles published in 2008-2012. *Research in Developmental Disabilities* 34, 10 (2013), 3618–3628. DOI: http://dx.doi.org/10.1016/j.ridd.2013.07.007

[22] Peter Olaf Looms. 2011. *Making Television Accessible*. Technical Report. Global Initiative for Inclusive Information and Communication Technologies, ITU. 92 pages.

[23] Shachar Maidenbaum, Daniel Robert Chebat, Shelly Levy-Tzedek, and Amir Amedi. 2014. Depth-to-audio sensory substitution for increasing the accessibility of virtual environments. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 8513 LNCS, PART 1 (2014), 398–406. DOI: http://dx.doi.org/10.1007/978-3-319-07437-5{_}38

[24] Taibbi Marzia, Cristian Bernareggi, Andrea Gerino, Dragan Ahmetovic, and Sergio Mascett. 2014. Audiofunctions: Eyes-free exploration of mathematical functions on tablets. In *International Conference on Computers for Handicapped Persons*. Springer, Cham, 537–544.

[25] Hisashi Miyashita, Daisuke Sato, Hironobu Takagi, and Chieko Asakawa. 2007. Aibrowser for multimedia: introducing multimedia content accessibility for visually impaired users. *Assets '07: Proceedings of the 9th international ACM SIGACCESS conference on Computers and accessibility* (2007), 91–98. DOI: http://dx.doi.org/10.1145/1296843.1296860

[26] Yarden Moskovitch and Bruce N. Walker. 2010. Evaluating text descriptions of mathematical graphs. In *Proceedings of the 12th international ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '10)*. ACM, 259–260. DOI: http://dx.doi.org/10.1145/1878803.1878860

[27] John G. Neuhoff. 2011. Perception, Cognition and Action in Auditory Display. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G. Neuhoff (Eds.). http://sonification.de/handbookhttp://www.logos-verlag.comhttp://sonification.de/handbook/chapters/chapter4

[28] Partnership On Employment and Accessible Technology (PEAT). N.D. Video Accessibility Principles. (N.D.). https://www.peatworks.org/content/video-accessibility-principles

[29] PhET Interactive Simulations. 2018. Phetsims/Tambo. (2018). github.com/phetsims/tambo

[30] PhET Interactive Simulations. 2019a. Molecules and Light. (2019). https://phet.colorado.edu/en/simulation/molecules-and-light

[31] PhET Interactive Simulations. 2019b. Ohm's Law. (2019). https://phet.colorado.edu/en/simulation/ohms-law

[32] PhET Interactive Simulations. 2019c. Resistance in a Wire. (2019). https://phet.colorado.edu/en/simulation/resistance-in-a-wire

[33] Noah S. Podolefsky, Emily B. Moore, and Katherine K. Perkins. 2013. Implicit scaffolding in interactive simulations: Design strategies to support multiple educational goals. *Arxciv* (2013), 1–30. http://arxiv.org/abs/1306.6544

[34] Hsiao Ching She and Yi Zen Chen. 2009. The impact of multimedia effect on science learning: Evidence from eye movements. *Computers and Education* 53, 4 (2009), 1297–1307. DOI: http://dx.doi.org/10.1016/j.compedu.2009.06.012

[35] Taliesin L. Smith. 2016. *Access, Action, & Agency: Inclusive Design for the Non-visual Use of a Highly Interactive Simulation*. Ph.D. Dissertation.

[36] Taliesin L Smith, Jesse Greenberg, Sam Reid, and Emily B Moore. 2018. Parallel DOM Architecture for Accessible Interactive Simulations. *Proceedings of the Internet of Accessible Things (W4A '18)* (2018).

[37] Taliesin L. Smith and Emily B. Moore. 2020. Storytelling to Sensemaking: A Systematic Framework for Designing Auditory Description Display for Interactives. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM. DOI: http://dx.doi.org/10.1145/3313831.3376460

[38] Volker Sorge, Mark Lee, and Sandy Wilkinson. 2015. End-to-end solution for accessible chemical diagrams. In *Proceedings of the 12th Web for All Conference*. ACM, 1–10. DOI:http://dx.doi.org/10.1145/2745555.2746667

[39] Robert David Stevens, Stephen A. Brewster, Peter C. Wright, and Alistair D. N. Edwards. 1994. Design and evaluation of an auditory glance at algebra for blind readers. (1994). Proceedings/1994/StevensBrewster1994.pdf

[40] Cary A. Supalo and Sean H. Kennedy. 2014. Using Commercially Available Techniques To Make Organic Chemistry Representations Tactile and More Accessible to Students with Blindness or Low Vision. *Journal of Chemical Education* 91, 10 (2014), 1745–1747. DOI: http://dx.doi.org/10.1021/ed4005936

[41] The Kennedy Center. 2013. *for People with Vision Loss*. Technical Report September. 36 pages.

[42] Brianna J. Tomlinson, Jared M. Batterman, Prakriti Kaini, Bruce N. Walker, and Emily B. Moore. 2018. Supporting Simulation Use for Students with Intellectual and Developmental Disabilities. *Journal on Technology and Persons with Disabilities,* 6 (2018), 202–218.

[43] Brianna J. Tomlinson, Prakriti Kaini, E. Lynne Harcen, Bruce N. Walker, and Emily B. Moore. 2019. A Multimodal Physics Simulation: Design and Evaluation with Diverse Learners. *Journal on Technology and Persons with Disabilities,* (2019).

[44] Brianna J. Tomlinson, Brittany E. Noah, and Bruce N. Walker. 2018. BUZZ: An Auditory Interface User Experience Scale. In *CHI'18 Extended Abstracts*. Montreal, QC, Canada. DOI: http://dx.doi.org/10.1145/3170427.3188659

[45] U.S. Department of Education - Office for Civil Rights. 2018. STEM course taking. April (2018), 1–12.

[46] Bruce N. Walker and Michael A. Nees. 2011. Theory of Sonification. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G Neuhoff (Eds.). Logos Verlag, Berlin, 9–39.

[47] WebAIM. 2018. Alternative Text. (2018). https://webaim.org/techniques/alttext/

[48] Evan F. Wies, M. Sile O'Modhrain, Christopher J. Hasser, John A. Gardner, and Vladimir L. Bulatov. 2007. Web-based touch display for accessible science education. In *International Workshop on Haptic Human-Computer Interaction*. Springer, Berlin, Heidelberg, 52–60. DOI: http://dx.doi.org/10.1007/3-540-44589-7{_}6

[49] R. Michael Winters, Brianna J. Tomlinson, Bruce N. Walker, and Emily B. Moore. 2019. Sonic Interaction Design for Science Education. *Ergonomics in Design: The Quarterly of Human Factors Applications* 27, 1 (2019), 5–10. DOI: http://dx.doi.org/10.1177/1064804618797399