Sonic Interaction Design for Science Education

Making physics simulations accessible to those with vision impairments demonstrates the effectiveness of applying sound.

By R. Michael Winters, Brianna J. Tomlinson, Bruce N. Walker, & Emily B. Moore

FEATURE AT A GLANCE:
The PhET project is a collection of over 130 interactive simulations (or "sims") designed to teach physics concepts to students from elementary to university levels. The sims rely heavily on visual representation, making them inaccessible to students with disabilities, including those with visual impairments. We present the theory, methods, and process behind our audio design and provide example mapping strategies from two of the simulations. We compare physical, abstract, and musical mapping strategies, noting the strengths of each. We conclude with design recommendations that have arisen in our work, and for which we think would benefit the field at large.

KEYWORDS:
education, training, simulation, auditory controls and displays, accessibility, music, mapping

Educational simulations are highly effective and widely used in today's classrooms to support student learning (D'Angelo et al., 2014; Scalise et al., 2011). Although quality simulations consist of an evidence-based presentation of pedagogical content, carefully designed visual representations, and intuitive interaction patterns, very few have comparatively rich auditory display features.

The PhET Interactive Simulations project (http://phet.colorado.edu/)at the University of Colorado Boulder has created a suite of over 130 free science and mathematics simulations. These simulations (or "sims") are used in classrooms from elementary school to university level. The sims are available in 90 languages and run over 80 million times a year by teachers and students around the world. Each PhET sim design includes dynamic interactivity, scaffolding and cuing for productive interactions, use of multiple representations, interaction with causal relationships, and opportunities for rapid inquiry cycles (Paul, Podolefsky, & Perkins, 2012). Unfortunately, their reliance on visual representations makes PhET sims not yet accessible to many students with disabilities, including students with visual impairments. Starting in 2014, the PhET project began an initiative to enhance the accessibility of the sims for students with disabilities, resulting in the development of sims with alternative input capabilities (e.g., keyboard navigation) and auditory description. From initial efforts in auditory description, the need for more robust auditory display to support visual and nonvisual access became apparent (Smith, Lewis, & Moore, 2016). Efforts in audio design have recently begun, with the goals of supporting engagement for students utilizing the visual display and supporting access and learning for students with visual impairments and other print-related disabilities.

BACKGROUND AND MOTIVATION

Auditory displays can support learning and scaffolding to create more accessible educational tools. Mansur, Blattner, and Joy's (1985) sound graphs provided one of the first auditory graphing systems available for helping blind students understand and interpret two-dimensional plots. These graphs were comparable to tactile graphs in accuracy but provided faster interaction and interpretation. Brewster's (2002) work has explored sonifying different types of data series, such as browsing two data series concurrently. More recently, GNIE (Graph and Number Line Input and Exploration) has provided an auditory alternative to tactile graphs for middle school students with vision impairment (Tomlinson, Batterman, Chew, Henry, & Walker, 2016).

Sonifications leverage initial understanding through metaphors used in their design, such as the temperature-to-pitch or size-to-tempo mappings (Walker & Kramer, 2005). Upson (2002) found that sonified graphs provided greater levels of engagement for students learning about visual graphs. Sonification can improve recall and recognition through careful sonic information design: mapping pitch to numeric values, using temporal patterns for sudden variability, and relying on loudness for categorical changes (not quantitative mappings; Flowers, 2005).

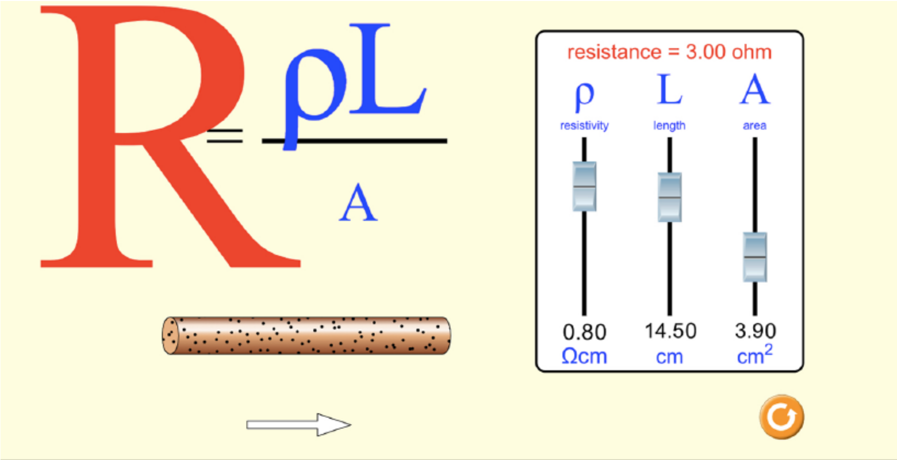

Figure 1. A screenshot of the PhET sim Resistance in a Wire, showing the equation and wire representations, and sliders. Used with permission from the PhET Interactive Simulations project. Copyright PhET Interactive Simulations.

DESIGN METHODOLOGY

Initial considerations. Leveraging previous work in inquiry-based learning and sonification design (e.g., Levy & Lahav, 2012), we propose the use of design-based research to support sonic information design (SID) for the PhET sims. Design-based research supports iterative and overlapping rounds of situated, frequent evaluations where input is gathered through qualitative and quantitative methods – leveraging the skills and feedback from participants as co-designers (Barab & Squire, 2004). It provides a flexible context for educators and researchers to work together during the design process and a framework of guiding principles for the design process (Wang & Hannafin, 2005).

We propose SID for educational access as having two fundamental axes: utility and experience. In a good design, both are maximized to the extent possible in a given context. For utility, the sounds should maximize the degree to which they can functionally convey information. This axis specifically addresses the utility as a means to represent data relationships; sounds that are simple, clear and quickly understood by listeners are ideal.

Alongside utility, a good sound design should maximize additional experience variables, such as engagement, enjoyment, and imagery. These variables pull the user into the simulation: engaging their attention, evoking feelings, and setting the auditory scene. A good analogy would be “style” or “genre” in music. Although this axis can benefit all users, its application should be tempered by ensuring that the needs of users with disabilities, particularly those with visual or cognitive impairments, are taken into consideration. Less salient sounds should not obscure more vital information, and auditory scenes should not be overly complex.

Altogether, in our work we have sought to determine what types of sounds and sonic parameters can most enhance the utility and experience of interaction across the range of simulations in the PhET project.

Process. Our design process was agile and proceeded through weekly collaborative meetings consisting of planning, prototyping, implementation, testing, and research discussions and reflection. The team consisted of two groups: one familiar with the design context, current approaches to accessibility, and software development, and the second consisting of sonification researchers familiar with auditory display research, design, and testing.

We prototyped ideas in a flexible manner, using SuperCollider, Max/MSP, GarageBand, and Ableton, often combining two tools simultaneously. For dynamic interactions, a special network bridge was created to link the visual simulation and the design language using Open Sound Control (https://github.com/fluid-studios/phet-osc-bridg). Live “demoing” formed the core of design presentations, and video examples were created for reference. Once a consensus of the best initial design or design options were reached, they were implemented on the Web through the use of a wrapper that allowed individual exploration and user testing. Once these designs are finalized, they will be built into the sims for publication and broad dissemination.

To illustrate these ideas, we present two example simulations: Resistance in a Wire and Balloons and Static Electricity.

TWO EXAMPLE SIMULATIONS

Resistance in a Wire. Resistance in a Wire, shown in Figure 1, is a physics sim focused on teaching the relationship between resistance R and three parameters: resistivity ρ, length L, and area A. In the visual sim, this relationship is represented in two ways, through a mathematical equation,

$$R = \frac{\rho L}{A}, \tag{1}$$

whose variables increase and decrease in size and with a physical representation of a wire that changes according to the physical meaning of the variables (see Figure 1). We narrowed

Table 1. Example Mapping Strategy for Resistance in a Wire

Parameter	Display Type	Mapping
Resistance	Music	Changing tempo
Resistivity	Physical model	Changing "bubble" density
Length	Physical model	Changing decay time
Area	Physical model	Changing pitch

the primary goals of SID to (a) conveying the linear and inverse relationships present in the mathematical equation and (b) conveying the context of the wire. Table 1 shows an example mapping.

We considered three basic audio designs: physical, abstract, and musical. In the physical design, changing resistivity, length, or area causes a physical model of a plucked wire to update. This physical design allowed a variety of subtle controls, but we used only a few of the most salient. We mapped increasing area of the wire to decreasing pitch, and increasing length to increasing decay time. To represent increasing resistivity, the wire was excited by short, soft, and raspy impulses, which would increase in density with increasing resistivity.

In the abstract sonic design, the goal was to clearly represent the user's continuous interaction with the visual sliders. For this purpose, the sliders were represented as three unique FM-synthesized timbres with equivalent pitch ranges. As the visual sliders slid up or down, the auditory sliders would increase or decrease in pitch, in a way similar to the continuous slide of a trombone.

We considered a third, "musical" approach for the resistance R. To begin, a variety of simple musical samples and sequences were created to reflect the "playful, simple, and kidlike" style. These samples were then looped continuously during user interaction with the sliders. As the resistance increased, the tempo would decrease, giving the impression that the music was "slowing down." Similarly, when the resistance decreased, the music would "speed up."

User feedback. We collected initial feedback from 57 (29 female) adult college students ages 18 to 37 (mean = 19.6 years) on the sound design options for Resistance in a Wire through two different Web surveys using six versions of the sim with various layers of embedded displays. Study approval was obtained through the university institutional review board (IRB), and each participant was given a documentation of waiver of consent providing information about the study before completing the survey. While using the sim, participants answered task-based questions, provided feedback on their comprehension of the auditory representations, and completed Likert questions reflecting on the auditory display's ease of use.

The slider mappings were understood across all sims, although it was a little harder for participants to understand the combined pitch-and-tempo-based resistance representations while listening to the pitch changes for the sliders. Reducing their volume in the second survey resulted in more participants correctly identifying the slider and resistance sounds. Of the five resistance mappings, the plucking sound (played at the end of the interaction) resulted in the highest percentage of students identifying it as resistance (up to 80% of respondents in Survey 2) and had the highest ease of concept relation. More in-depth reporting about the results of this study will be in a forthcoming conference paper.

Balloons and Static Electricity. Balloons and Static Electricity is also a physics sim and focuses on teaching concepts related to static electricity. The visual display opens with a yellow balloon in the center of the screen, a sweater to the left, and a wall to the right (see Figure 2). Each object has positive and negative charges, represented by blue and red circles. Picking up and rubbing the balloon on the sweater causes negative charges from the sweater to be transferred to the balloon. When released away from the sweater, the negatively charged balloon will drift toward, and stick to, the sweater. Moving the negatively charged balloon toward the wall results in the negative charges on the wall being repelled, creating an induced positive charge. The primary goal of SID for this sim was to convey the location of the balloon (a particularly challenging feat through text description) to support users with visual impairments.

As in Resistance in a Wire, we considered both abstract and physical representations in our design. In the abstract design, the (x, y) location of the balloon was the data parameter. In the sim's underlying model, kinetic and potential energy were the parameters being used to determine the location of the balloon in the sim's electric field. We focused on SID of these parameters, along with some short sounds to correspond to direct actions, such as picking up and dropping the balloon (see Table 2 for an example mapping).

To represent the potential energy of the balloon, we chose a musical loop, which would increase in loudness with increasing potential. For kinetic energy, we used filtered white noise to create a "whoosh" sound, which increased in loudness with increasing velocity. These two sound sources would play concurrently when the balloon drifted back to the sweater. To represent the deflection of electrons on the wall (induced charge), we modified the playback rate of the looping sound clip, increasing the rate with amount of deflection.

User feedback. We conducted semistructured interviews with 11 (four females) students (three with vision impairment) ages 16 to 23 (mean = 19.9 years) using Balloons and Static Electricity. Study approval was obtained through the university IRB, and each adult participant completed a consent form before beginning the interview; minor students provided assent after parental permission was obtained. During these interviews, the students were given 5 min for free exploration, where they could use whatever components of the sim they

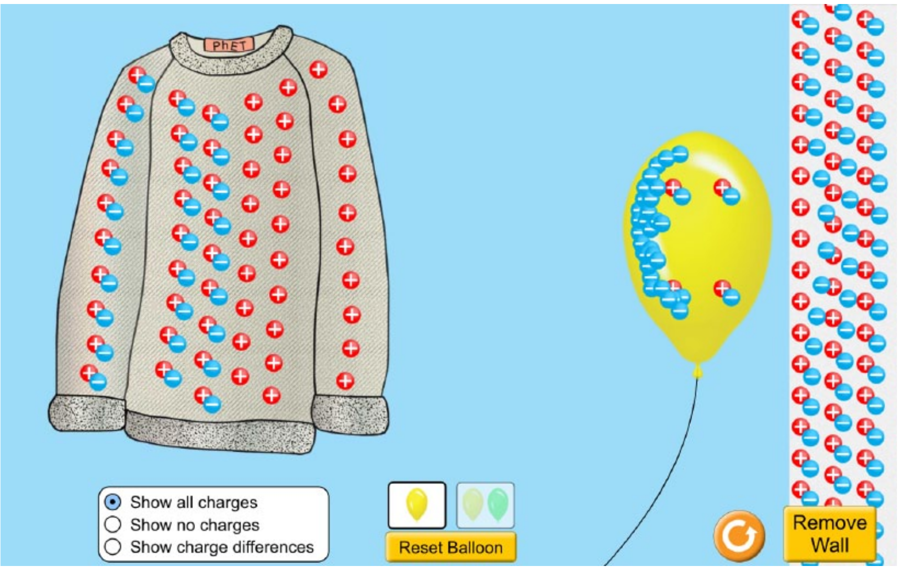

Figure 2. A screenshot of the PhET sim Balloons and Static Electricity, with an induced charge along the wall. Used with permission from the PhET Interactive Simulations project. Copyright PhET Interactive Simulations.

Table 2. Example Mapping for Balloons and Static Electricity

Parameter	Display Type	Mapping
Kinetic energy	Physical model	Increasing volume
Potential energy	Music	Increasing volume
Induced charge	Music	Increasing playback rate
Balloon pickup/drop	Earcon	Tonic/dominant
Hitting wall	Auditory icon	Sound of "bumping"
Rubbing on sweater/wall	Physical model	Velocity to volume

wanted, and were prompted to think aloud while using the sim (see Tomlinson, Batterman, Kaini, Walker, & Moore, 2018, for more details about these studies). None of the students with vision impairment mentioned the changes in volume relative to the kinetic and potential energy changes. The representations for induced charge, the balloon, and its kinetic movement all successfully supported nonvisual interaction.

DISCUSSION

A challenge for both simulations was determining what aspects of the visual scene needed to be conveyed and which were secondary or even unnecessary. Each simulation was rendered using many data properties, and prioritizing the design based upon the desired learning concepts focused this selection.

Both designs were presented in terms of "physical," "abstract," and "musical" options. There are strengths inherent in each. In the opinion of the authors, physical mappings rendered interesting results with clear relationships to the visual simulation. In the case of Balloons and Static Electricity, the physical approach simplified the problem of communicating *where* a balloon was. However, these physical designs were not always the most appropriate. For example, pitch change is a strong and clear auditory variable, and its application in the abstract representation of the sliders in Resistance in a Wire were the easiest to interpret.

The presence of music in sonification is always an interesting point of discussion (Vickers, 2017), and its incorporation offers a moment to reflect on the two design axes from our Design Methodology. Functionally, we noted that the tempo and playback rate (pitch) of looping musical clips could convey desired learning concepts. Experimentally, musical samples helped creating sonic environments that were "playful, simple, and kidlike." From these observations, music seems to be particularly adept at addressing both design axes.

DESIGN RECOMMENDATIONS

Prototype in design languages. When beginning, there are an infinite number of possible designs. Producing compelling examples and prototyping demos provides an agile work flow. At this point, there are many wrong turns and alternative ideas that will not make it to the final design. To sample from the design space rapidly, designs should progress in whatever language the designers are most fluent and not be encumbered by the technical constraints of the final implementation. Our designers were most comfortable in SuperCollider and Ableton, and allowing them to write their ideas in those languages first allowed many ideas to be articulated in short succession.

It may seem like a time savings to write only once and not translate between languages; however, technological challenges can slow down the process, and wrong turns can take longer to identify. A slower process will also mean fewer ideas, less diversity, and ultimately, a more limited palette for the context. Once the design is refined and stabilized, finalizing the implementation will be more linear.

Cultivate high-fidelity soundscapes. Auditory scene analysis demonstrates the unique capacity for users to parse a complex auditory scene composed of many sources operating in parallel (Bergman, 1990). In practice, memory and attention limit the number of sources that can be understood in parallel, and each new stream of auditory information requires exponentially more cognitive resources.

Pioneered by Schafer (1994), the *soundscape* refers to the sonic environment that surrounds us. A low-fidelity soundscape occurs in noisy areas, like cities, where it is very difficult to hear because of noise pollution. On the other hand, a high-fidelity soundscape is found in quiet places, like nature or the library, where the silence affords us the ability to attend to the subtleties of each sound. In SID, cultivating a high-fidelity soundscape is like cultivating silence. Great detail, attention, and clarity are achieved by removing complexity, parameters, and sources. Often there were cases where we wanted to convey multiple parameters simultaneously. Removing unnecessary or redundant sounds made the final design much clearer and more understandable.

Structure, then timbre. The two design axes, utility and experience, can be mapped to structural and timbral design. Structural design is the de facto sonification design supporting functional interpretation. It occurs during transformation of data sources through pitch, loudness, duration, rhythm, and spatial location.

Timbral design explores the experience: the effect of setting a mood, style, or *qualia* or shaping the user's experience at a broad level. Once we determined a structure that worked, we refined our timbral design to produce the most desirable experience.

CONCLUSION

The PhET Interactive Simulations project provides an interesting application for SID. As we continue our audio design on more sims, we are conducting user testing with low-vision, blind, and sighted populations to assess the success of our mappings. Our goal is to create guidelines that can be generalizable across PhET sims and other learning resources.

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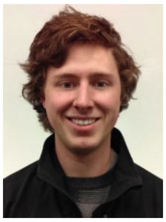

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