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# Breaking Down the Visual Barrier: Designing Data Interactions for the Visually Impaired in Informal Learning Settings

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**Abstract:** As data literacy takes an increasingly prominent role in education, learning sciences research is investigating how environments can be designed to foster sensemaking, including in informal environments. Yet, most efforts rely on visually-based data representations that remain inaccessible to blind and low vision learners. Work in human-computer interaction has explored solutions for human-data interactions that are accessible to visually impaired learners, but few have explored the intersection of data, informal learning, and visual impairment. Because informal science engagement is a strong influence toward developing STEM identities and pursuing STEM careers, neglecting to design informal science interactions for visually impaired learners can have long-term impact on participation in science. Here we review efforts toward supporting human-data interactions with scientific data for visually impaired learners, describe our interdisciplinary design efforts creating accessible auditory displays of oceanography data, and lay out an agenda toward designing accessible informal data interactions.

## Introduction

Work in the Learning Sciences has increasingly attended to strategies for developing data literacy across multiple contexts (Wilkerson & Polman, 2020), including designing human-data interactions (HDI) in informal learning environments (ILEs). Though an increasing number of data exploration exhibits are being implemented and studied in free-choice settings like museums, designing open-ended *organic HDI* experiences (Cafaro & Roberts, 2021) is a known challenge: users face difficulties in decoding unfamiliar data (Borner et al., 2016) and are rarely observed to correct their mistakes (Ma et al., 2019). Many exhibits draw on novel and collaborative interaction modalities such as multi-touch tables (Ma et al., 2019) and full-body interactions (Roberts & Lyons, 2020) to leverage embodiment and collaboration to support sensemaking. However, most data presentations in ILEs still rely on visual display techniques such as graphs and charts as their output, essentially excluding blind and low vision (BLV) learners from the informal engagements with science that are known to spark interest in STEM (Vela et al., 2020).

Solutions such as auditory display techniques, tactile graphics, and haptic feedback systems have the potential to transform how BLV learners perceive and make sense of data, but little research has integrated and implemented these display techniques in ILEs. Here we review the problem space of designing HDI for BLV learners and lay out an agenda for more accessible HDI in informal learning environments based on findings from our interdisciplinary design efforts with scientists, teachers for BLV learners, and BLV adults toward creating accessible visualizations for ILE's.

## Technologies Supporting Data Interactions for Blind and Low Vision Learners

Blind and low vision learners face data interpretation challenges above and beyond those faced by sighted peers for a variety of reasons. To start, many BLV students are provided fewer data literacy activities in formal school environments (Zebehazy & Wilton 2014), with some teachers reporting avoiding graphics on screens altogether (Choi et al., 2019). Barriers include limitations in cost, time, and effort (e.g. Melfi et al., 2020; Tomlinson et al., 2016); lack of materials and instruction (Bell & Silverman, 2019); lack of alt text captions in online materials (Choi et al., 2019); and inability to interact with data representations (Torres & Barwaldt, 2019). Yet, efforts in computing and visualization communities are creating accessible data visualizations for BLV learners to increase inclusion in STEM education. Here we review literature found through searches of ACM, IEEE, and Google Scholar for publications dated 2018 or later. Additional articles from 2013-2017 describing relevant topics not recently explored in publications were later included. We describe three primary methods of alternative access for BLV populations and discuss their potential applicability to ILE's.

### Audio Description

Audio description is an important feature for BLV users, as screen readers and text are the most popular access methods reported in a systematic review on diagram accessibility (Torres & Barwaldt, 2019). Teles De Oliviera et al. (2019) discussed bar chart audio standardization to optimize understanding, finding that information was best recalled when fewer than seven elements were described. In many ILE's, audio descriptions are prevalent in the form of audio tours or to provide non-visual interactions of some content, for example fine art (Vaz et al. 2018), but they are limited in their ability to support the social and collaborative learning known to be integral to informal environments. Future work must determine how to layer audio descriptions without excluding listeners from the social context of an ILE experience.

### Printed Tactile Graphics & Haptic Vibration Feedback

A large body of work has investigated tactile graphics, which use raised lines and surfaces that can be navigated by touch and are frequently reported as useful by teachers (Capovilla & Hubwieser, 2013) Printed graphics, however, are static and cannot dynamically update to include additional data. Furthermore, descriptive Braille can lead to sensory overload if included on the graphic but if not included, users must disengage from the graphic to read it, and labels are often difficult to associate with data (Braier et al., 2015; Melfi et al., 2020). Features making tactile graphics, and particularly charts, easier to understand is an area of active exploration as 3D printing becomes more cost effective and readily available.

Similarly, the prevalence of mobile phones and tablets with vibration capabilities have spurred further research on haptic feedback. However, limited availability of free haptic libraries and lack of customizable vibration options have limited the work in this area. Yet, because many ILE's—especially science centers—focus on tangible, hands-on interactive experiences to engage learners, tactile graphics and haptic feedback are a natural fit for such spaces. However, finding ways to make them collaborative and to easily provide important contextual information is key to effectively integrating such displays into informal learning environments.

### Sonification

Data sonification, or the mapping from data to one or more parameters of an audio signal, is gaining traction, particularly when used in conjunction with other types of non-visual output (Lahav et al. 2018, Smith & Moore 2020, Tomlinson et al. 2016; Winters et al. 2020). Tonal output is continuous and can play in the background of discrete speech signals, similar to how visual graphics use simultaneous perception of color and size to convey data efficiently.

Sound design has played an increasingly prominent role in ILE's as the "culture of sound" in museums has shifted from the silent museum to environments mediated by layers of narrative and ambient soundscapes that can "contribute to the closer interaction between visitors and exhibitions, generating knowledge through embodied and affective experiences of the museum space" (Bubaris, 2014). How sonification and auditory displays can be integrated into exhibit experiences, however, remains an open question, as the focused attention and high-quality hardware (e.g. headphones with support for binaural panning) typically used for sonification exploration may be difficult to support in a museum setting.

### Summary

Our review found a lack of evidence-based design focused on meeting the needs of visitors to ILEs who may not be able to see or decode quantitative information. Open questions also remain about how tools can be created that can facilitate collaborative interactions between BLV students in learning environments (Torres & Barwaldt 2019). This problem space at the intersection of HDI, visually impaired learners, and informal science is the focus of our work, described next.

## Auditory Data Displays to Make Oceanography Accessible

We are exploring the viability of creating auditory displays that are accessible to visually impaired learners in ILEs. Our interdisciplinary research team with expertise in sound design and data sonification, ocean science, learning sciences, and human-computer interaction is conducting an iterative design process with BLV learners, their teachers, and ocean scientists through a multi-faceted design process.

### Preliminary Work

We began by holding a group design session with five ocean science experts and one-on-one discussions with two additional dataset experts to elicit insights and suggestions on each dataset. We then conducted a 90-minute interview with two teachers for the visually impaired to elicit information on how they use sound in their classroom and engage their students with data. Our sound designer used this feedback to create multiple sonic foundations (sound mappings) to represent each key construct in our datasets. To choose the most appropriate pairing between these foundations and the scientific concepts they represent, we created an online survey to collect feedback from scientists, educators, visually impaired potential users, and members of the general public. Based on responses from 49 participants (including 12 screen reader users) we narrowed the scope of sound directions to create preliminary auditory display prototypes.

### Feedback Sessions on Auditory Display Prototypes

Feedback from the preliminary work informed the development of auditory display prototypes for three datasets. We recruited two additional teachers (T1, T2) of BVI students and two BVI adults for semi-structured interviews to review these prototypes. We played the sonification prototypes and asked for their reactions, suggestions, and thoughts on potential interactions that could work for students. These interviews gave us insights for future design iterations. Two primary emergent themes are described below.

#### *Support for collaborative learning* is needed

Teachers reported that blind and visually impaired students often struggle to learn on their own and prefer collaborative learning. “Independent academic work is a challenge for them sometimes. They really love discussions… they love having a topic, talking and brainstorming.” (T1) Since it is widely acknowledged that learning in ILEs is fundamentally a social process, collaborative technologies for BLV learners would be a natural match to these environments. Yet many auditory displays require headphones for full access, which can be isolating, and tangible objects must be designed to allow multiple users to interact simultaneously.

#### *Information and experience must be balanced*

Both teachers emphasized that BLV students are often behind grade level in science, causing them to struggle with some foundational concepts. T2 noted, “We would just need maybe a little bit of pre-teaching on some of the terminologies.” These challenges are parallel to those in ILEs where visitors bring a diversity of backgrounds and prior knowledge, and exhibits must introduce concepts quickly. However, too much introductory material can be off-putting, particularly in ILE’s, which require quick engagement or visitors lose interest. One adult BLV tester reported getting a bit lost with the amount of introductory speech in one of our auditory displays.

## Open Questions for Future Work

The growing attention to designing accessible data visualizations and accessible informal learning environments has not yet converged to address how data exploration activities can be designed for blind and visually impaired learners in informal settings. Our review of existing technology and our interdisciplinary design research to date has uncovered multiple key questions to guide future efforts in this area.

### Interactive versus Static Sonifications

Our current sonification prototypes lack interactivity. Teachers and BLV adults suggested adding control over the auditory displays to enhance interest and learning, taking into consideration the variations among BLV learners in their visual perception capabilities and their familiarity with assistive devices. An interactive system with a low barrier to entry can provide agency and data exploration experiences for meaningful sensemaking interactions.

### Sonification Design and Aesthetic

Although our sonification prototypes were composed by a music technologist, questions remain regarding the integration of auditory displays into the museum culture of sound (Bubaris, 2014). Further study is needed to determine the optimal balance between engagement and understandability in a sonification, as well as the potential for additional audio layers without overwhelming the listener's comprehension.

## Conclusion

Although audio modalities like music, sound effects, and environmental noises are occasionally employed in ILEs to engage learners, they are typically incorporated as ambient noise or narration and less frequently convey quantitative information. Data sonification has the potential to change how ILE visitors interact with and comprehend data, yet there is minimal study on the most effective ways to integrate and apply these display techniques in ILEs. Our approach to address this gap is through design with teachers of BLV students, BLV learners, and scientists, in collaboration with an interdisciplinary design team.

A review of literature on human-computer interaction, visualization, and informal learning as we began this work revealed a breadth of research in each discipline with very little intersection across communities. We see this gap in cross-disciplinary communication as an opportunity for the Learning Sciences community, with its deep interdisciplinary expertise and equity-driven focus, to investigate this under-researched space.

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