ITERATIVE DESIGN OF AUDITORY DISPLAYS INVOLVING DATA SONIFICATIONS AND AUTHENTIC OCEAN DATA

Jon Bellona

School of Music and Dance
University of Oregon
Eugene, OR, USA
jbellona@uoregon.edu

Huaigu Li

College of Computing
Georgia Institute of Technology
Atlanta, GA, USA
huaigu.li@gatech.edu

Jessica Roberts

College of Computing
Georgia Institute of Technology
Atlanta, GA, USA
jessica.roberts@cc.gatech.edu

Amy Bower

Woods Hole Oceanographic Institution
Woods Hole, MA, USA
abower@whoi.edu

Leslie Smith

Your Ocean Consulting
Knoxville, TN, USA
leslie.smith@youroceanconsulting.com

ABSTRACT

The “Accessible Oceans” pilot project aims to inclusively design auditory displays that support perception and understanding of ocean data in informal learning environments (ILEs). The project’s multi-disciplinary team includes expertise from all related fields— ocean scientists, dataset experts, a sound designer with specialization in data sonification, and a learning sciences researcher. In addition, the PI is blind and provides a crucial perspective in our research. We describe the sound design of informative sonifications and respective auditory displays based on iterative design with user input at each stage, including from blind and low-vision (BLV) students, their teachers, and subject-matter experts. We discuss the importance of framing data sonifications through an auditory presentation of contextual information. We also report on our latest auditory display evaluation using Auditory Interface UX Scale (BUZZ) surveys at three ILE test sites. These responses further affirm our auditory display design developments. We include access to the auditory displays media and lessons learned over the course of this multi-year NSF-funded Advancing Informal Stem Learning (AISL) grant period. https://accessibleoceans.whoi.edu/

1. INTRODUCTION

To inclusively design auditory displays of ocean data for informal learning environments (ILEs), we took a highly collaborative approach. We employed specialists in the following domains including but not limited to: sonification, sound design, and audio production; learning sciences and interaction design; ocean science research and education; data science; and the BLV community. In the development of our auditory displays, we foregrounded data context [1] [2] and user-driven design [3]; the project also emphasized iteration and rapid evaluation [4].

1.1. Sonification and Informal Learning Environments

There are gaps in scientific and data literacy in the US, which create barriers for understanding science [5]. There is a need to contextualize quantitative data for all learners; however, ILEs exhibiting data visually presents decoding challenges even for sighted individuals [6]. In addition, for BLV learners, the lack of formal school data literacy activities exacerbates their interpretation challenges in museum settings [7]. Museum exhibits that do include sound in the displays to convey information about the natural world mainly rely upon qualitative elements — music and/or environmental sounds — in their auditory design (e.g., [8] [9]). Sound research demonstrates the ability to expand access in ILEs [10], provide powerful learning tools [11], and fit within ILE exhibit design [12]. We focused on designing contextualized auditory displays with informative sonifications to pilot their feasibility for a larger future museum exhibit. Even though our project focused on data literacy, BLV users, and ILE settings, the interdisciplinary process, our evaluations, and the iterative feedback yielded larger lessons applicable to a broad community across fields and settings.

1.2. Authentic Data: OOI Nuggets

Curated datasets that highlight specific ocean phenomena can help to focus educational efforts [13]. To this end, the NSF-funded Ocean Observatories Initiative (OOI) Synthesis & Education project (OCE-1841799) launched a set of freely available curated OOI datasets called the “OOI Nuggets.” Developed by co-author Smith, OOI Nuggets are discrete datasets pulled from the immense and continuous stream of OOI data that have been processed, quality controlled, and packaged to be used in classrooms [14]. Building upon this prior research, our project relied on a subset of these curated datasets, which then freed attention toward the design of auditory displays.

1.3. Auditory Display and Core Lessons

Each auditory display in our project (Table 1) revolves around an OOI dataset that reveals an important ocean phenomenon [14]. Each display follows a script based on core lesson takeaways for each OOI dataset. These core lessons were developed as part of initial design interviews with subject-matter experts and BLV educators. For example, the core lessons for air-sea carbon dioxide (CO_2) exchange are: (1) CO_2 goes in and out of the ocean, like breathing; (2) the exchange of CO_2 changes with the seasons in some ocean regions—colder winter water absorbs more CO_2 while warmer summer water outgasses CO_2; and (3) in some ocean regions where the temperature is cold all year long, CO_2 is absorbed in all seasons. All auditory display elements, including data sonifications, were built after core lessons had been developed. Table 1 provides links to the auditory displays, Table 2 details the track breakdown of the final versions, and Figure 1 shows the conceptual audio segments of our auditory displays, all of which were built through a user design process (section 2.1).

Table 1. Auditory Display Media

OOI Nugget	DOI Zenodo
2015 Axial Seamount Eruption	10.5281/zenodo.8173836
Long Term Axial Inflation Record	10.5281/zenodo.8173859
Net Flux of CO_2 Between Ocean and Atmosphere	10.5281/zenodo.8162769
Zooplankton Daily Vertical Migration Gets Eclipsed	10.5281/zenodo.8173914
Extratropical Storm Hermine	10.5281/zenodo.8173880

2. METHODS

2.1. User Input

Our inclusive design process involved various rounds of external feedback and user input. In chronological order, these users and sessions were (1) oceanography expert interviews with PhD scientists having specialized knowledge; (2) BLV teacher interviews at a partner school for the blind; (3) an informal Sonic Foundation survey using an online, accessible Qualtrics survey; (4) initial display prototype feedback interviews with two BLV adults and two teachers of BLV students; (5) feedback sessions with middle and high school BLV students; (6) broader community feedback with public presentations, Zoom calls, and in-person discussions; and (7) evaluative testing with users at three different informal learning environment sites (Georgia Aquarium in Atlanta, Eugene Science Center in Oregon, and the WHOI Discovery Center in Woods Hole, MA). This paper reports findings from in-person evaluative testing with BUZZ scale surveys from this seventh round. We discuss prior design rounds in detail in publications [15] [16] [17].

2.2. Technical Setup

All the data sonifications for Accessible Oceans were created with the Kyma hardware/software environment running at 48k 24-bit [18]. We recorded narrations using a Sennheiser MKH 416 mic in a low-noise home studio and recorded at the same sample rate and bit depth as Kyma. We generated spoken markers using the "Sam (US)" voice by Speech Synthesis via Web Speech API on Chrome. We created a small library of these common axis-marker sounds and made them publicly available on GitHub [19]. Additional earcons were made using Logic Pro X or Kyma. The underlying music used in the displays was licensed using a royalty-free service [20]. The auditory display elements — recorded dialog, data sonifications, music, spoken markers, and earcons — were placed on separate audio tracks inside Logic Pro X to allow control over production decisions. All auditory displays were edited, mixed, and mastered using Logic Pro X. Third party plugins used in mixing and mastering include effects from the FabFilter bundle, iZotope production suite, Kush audio, and Plugin Alliance. Audio production experience — workflow and tools — was integral to the iterative completion of deliverables.

2.3. Sonification Methods and Designs

We used three basic methods inside Kyma to transform data files into time-based control data that was sample accurate. The first method involved transforming the CSV data files into audio signals, which were then read as audio rate wavetable control signals at user-specified durations. We desired real-time user-control of parameters, duration, and data file selection to assist with sonification design. The second method involved reading data files with the *AudioFromData* Kyma Sound object. We created variables within the object's *MappingFunctions* parameter field and within Kyma *SoundToGlobalController* Sound objects, which could then control any number of parameters across other Kyma Sounds. Again, real-time control of parameters assisted in sonification design. The third and less used method involved reading data files with the *TimeIndexedEventsFromData* Kyma Sound object, where each row of data had the potential to become an audible sound event. We employed these three methods to serve the exploration of new and alternative ideas.

Examples of mapping include, but are not limited to:

- amplitude and frequency of noise generator mapping along with parametric EQ boost mapping (Net Flux of CO_2 between Ocean and Atmosphere);
- spectral filter of noise resynthesis mapping (Long Term Axial Inflation Record);
- frequency and amplitude of oscillator mapping (Daily Vertical Migration, Extratropical Storm Hermine);
- period rate, high-pass filter frequency cutoff, stereo-width, and amplitude mapping of noise (Daily Vertical Migration);
- event-based threshold triggers (2015 Axial Seamount Eruption, Long Term Axial Inflation Record; Extratropical Storm Hermine);
- fractal noise filter frequency cutoff mapping (2015 Axial Seamount Eruption);
- hard panning to separate sonification layers (Net Flux of CO_2 between Ocean and Atmosphere);
- data threshold dependent sound design (Net Flux of CO_2 between Ocean and Atmosphere);

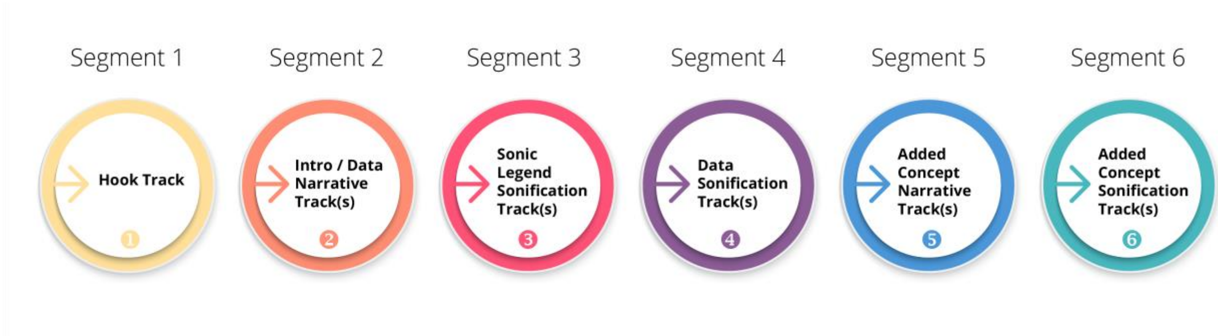

Figure 1: Auditory Displays Conceptual Segments Outlining Basic Track Order

Table 2. Auditory Display Media Track Breakdown with Segment Numbers Bulleted (Final Versions)

2015 Axial Seamount Eruption	**Long Term Axial Inflation Record**	**Net Flux of CO_2 Between Ocean and Atmosphere**	**Zooplankton Daily Vertical Migration**	**Extratropical Storm Hermine**
10 tracks. 7m 11s	13 tracks. 7m 5s	7 tracks. 6m 20s	9 tracks. 8m 2s	21 tracks. 9m 20s
① Hook track ② Tidal Cycle Intro pt.1 ② Tidal Cycle Intro pt.2 ③ Sonification: 1 day ③ Sonification: 1 week ② Eruption Intro ④ Sonification 1 month ④ Sonification with Eruption Marker ⑤ Combined Phenomena Overview ⑥ Sonification x2 speed	① Hook track ② Introduction pt.1 ② Introduction pt.2 ③ Sonification Context ③ Legend: Eruption ③ Legend: Seafloor ④ Sonification 1997-2011 ④ Sonification 1997-2021 ⑤ Inflation Threshold Introduction ⑤ Legend: Threshold ⑥ Sonification 1997-2021 Threshold ⑤ Debrief ⑥ Sonification Replay	① Hook track ② Introduction pt.1 ② Introduction pt.2 ③ ④ Legend: Outgassing, and Sonification ③ ④ Legend: Absorption, and Sonification ④ Sonification: Both Phenomena ⑤ ⑥ Sonification: New Location, Both Phenomena	① Hook track ② ③ Solar Intro and Legend ② ④ Eclipse Intro and Sonification ④ Sonification Replay ⑤ Zooplankton Intro ⑤ ⑥ Legend: Zoo. And Sonification ⑥ Solar & Zooplankton Sonification ⑥ Eclipse & Zooplankton Sonification ⑥ Sonification Replay	① Hook track ② Introduction pt.1 ② Introduction pt.2 ③ Legend: Rain ④ Sonification Rain ③ Legend: Wind ④ Sonification: Wind ⑤ Wind & Rain ⑥ Sonification: Wind & Rain ⑤ Legend: Waves ⑥ Sonification: Waves ⑤ Wind, Rain, Waves ⑥ Sonification WRW ⑤ Wave Outro ⑤ Temperature Intro ⑥ Sonification: Temp. ⑤ Temp. & Waves ⑥ Sonification: Temp & Waves ⑤ Temp. Outro ⑤ All Phenomena ⑥ Sonification: All

- "slo-mo" time warping to focus on a period of data (Extratropical Storm Hermine, Daily Vertical Migration).

2.4. Sonification and Auditory Display Development

The development of the data sonifications and their accompanying auditory display elements was an iterative process. We discuss the multiple iterations, user groups, surveys, and feedback in detail within publications in the Conference on Computer-Supported Collaborative Learning proceedings [15], SIGACCESS Conference on Computers and Accessibility [16], and *Oceanography* magazine [17], as well as on our Accessible Oceans blog website [21]. Our latest evaluative testing, using the Auditory Interface UX BUZZ Scale [22], will be discussed below in Section 2.5. Each auditory display element — data sonifications, narration, music, spoken markers, earcons — received some external feedback during the project, whether through informal surveys, interviews, and conference activities, or from formal surveys and testing. In summary, all Version 1 auditory displays were made after three rounds of user input (Section 2.1). Version 2 auditory displays were updated at various times based on work in subsequent rounds (see rounds 4, 5, 6, and 7 in Section 2.1 and see Table 3). For Version 2 we updated all auditory display scripts and added "hook" tracks, which are short audio clips designed to engage the listener. We achieved consistency across displays in Version 2 by making sure all sonifications included earcons to mark the start and end of playback [23] and by mastering the display audio. Version 3 denoted sonification design updates and were made based on our last two rounds of user input (see Section 2.1). Only the

Table 3. Auditory Display Site Testing, showing Version and Sample Size

Test Site	2015 Axial Seamount	Axial Long Term Inflation	Net Flux of CO_2	Daily Vertical Migration	Storm Hermine
GA	v2.0 full N = 7	v1.0 (short) N = 6	v1.0 N = 8	v1.0 N = 8	N/A
ESC	N/A	N/A	N/A	v2 (subset) N = 6 "hook" track; script updates; sonification wrapper earcons; mastering	v2.1 (subset Rain & Wind) N = 3
WHOI	v2.2 (subset) N = 9 sonification wrapper earcons; remix levels, mastering, script updates	v2 (short) N = 3 new narrator, script updates, updated track order	V3.0 (subset) N = 5 new absorption design; sonification wrapper earcons; mastering; script updates; "hook" track	v2 (subset) N = 9	v2.1 (subset Rain & Wind or subset Wind & Waves) N = 12

Extratropical Storm Hermine and Net Flux of CO_2 between Ocean and Atmosphere displays received a Version 3 update.

All auditory displays are between six to nine minutes in length and are comprised of several audio segments (Figure 1). Audio tracks are divided based on script and content (Table 2). The final versions of our displays consist of an introductory "hook" track, data narrative context track(s), sonic legend track(s), data sonification track(s), and then additional data narratives and data sonifications depending on the specific data sets and core lessons.

The data sonification tracks consist of informative sonifications mixed with spoken axis-markers or event earcons and all sonifications have earcons [23] that mark the beginning and end of sonification playback. At times the sonification tracks include spoken narration that further contextualize data before or after the sonification. All auditory displays are available for download on Zenodo and can be streamed online via Samply media players (see Table 1 for links, with media players on respective Zenodo pages).

2.5. BUZZ Scale Testing in Informal Learning Sites

BUZZ Scale is an audio user experience (UX) scale, designed to evaluate the user experience of an auditory user interface [22]. The eleven questions in this scale can be used to measure the "enjoyment and appeal" and "ease of use" of the auditory user interface design. For each question, the participant reports the answer from 1 (Strongly Disagree) to 7 (Strongly Agree).

We conducted formal testing sessions via interviews to evaluate our auditory display prototypes. All sites used Sony MDR-7506 headphones for listening activities. The first testing session was conducted at the Georgia Aquarium (GA). In the first session, participants were tested individually or in pairs. Testing size was based on the visitor group size. Some visitors were traveling alone, or only one person in a group consented. Headphone splitters allowed pairs to listen to the same material at the same time. We initiated the testing by asking pre-knowledge questions to evaluate their prior knowledge (e.g. "Do you know about the ocean carbon outgassing and absorption process?"). Then the participants listened to the auditory display prototypes with the option to

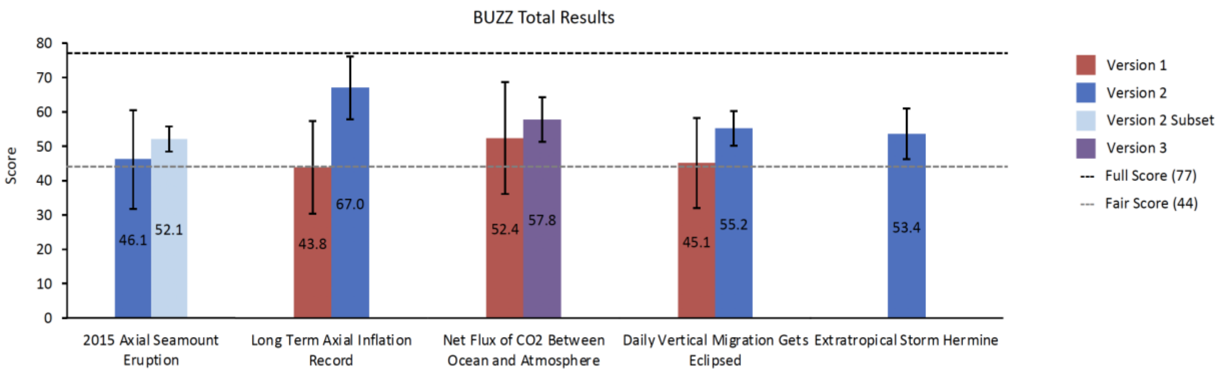

Figure 2: BUZZ Scale Total Results for five Auditory Displays

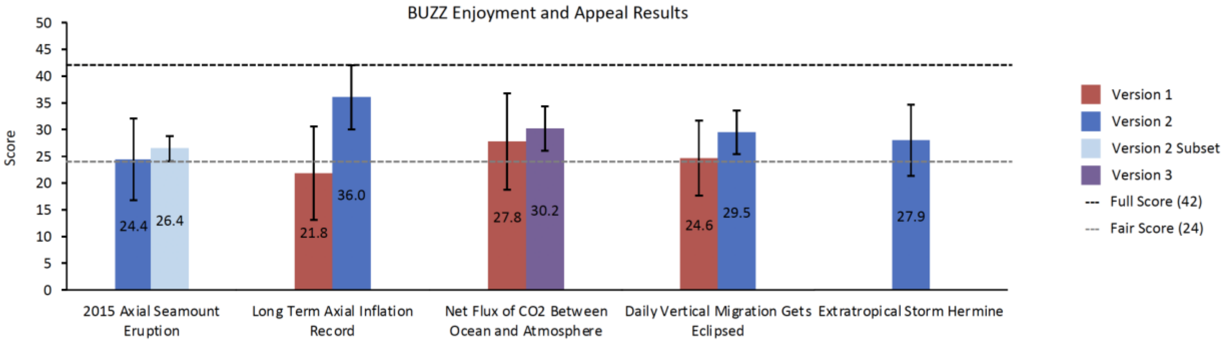

Figure 3: BUZZ Scale "Enjoyment and Appeal" Results for five Auditory Displays

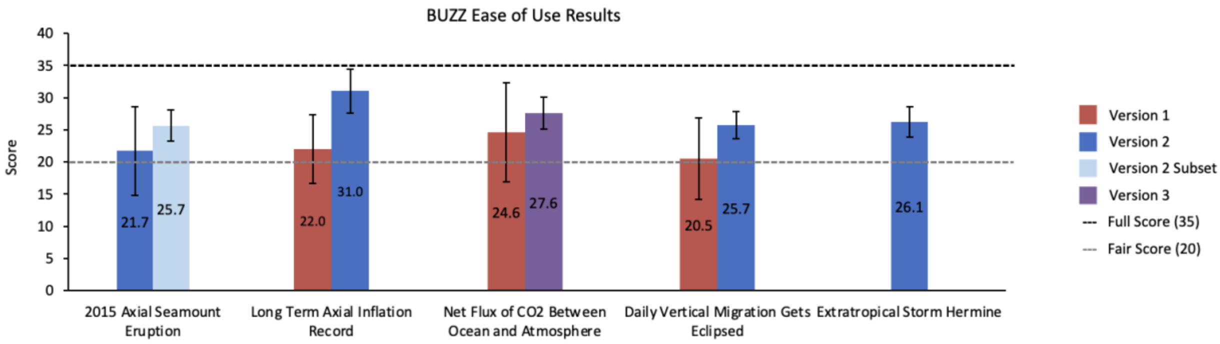

Figure 4: BUZZ Scale "Ease of Use" Results for five Auditory Displays

re-listen if necessary. Participants were then asked questions tailored to each display to measure learning outcomes (e.g. "What happens when the seafloor drops?"). After the interview, participants completed a survey including demographic questions and the BUZZ Scale questions. The second and third testing sessions were conducted at the Eugene Science Center (ESC) and the WHOI Discovery Center (WHOI). The primary focus in these settings shifted toward collecting feedback related to user experience. We presented one or more auditory displays to participants, either in pairs or individually, then conducted interviews to assess participants' experiences and impressions (e.g. "What do you think of the background music and the narration?"). Participants were allowed to re-listen to the auditory displays if needed. Following the interviews, participants completed the same survey used in the first testing session. Interviews in the three sessions were audio-recorded and manually transcribed. The results of the interview were then qualitatively analyzed and provided suggestions to revise our prototypes.

3. RESULTS

3.1. Data Processing

We collected a total of 76 unique BUZZ Scale responses across the five auditory displays and across the three testing sites (see Table 3). Each response represents one user. We collected vision condition, hearing condition, and the range of user's age; however, without a large enough sample size for BLV visitors, we did not compare between BLV visitors and sighted visitors. As the time of writing, we are conducting a large-scale accessible Qualtrics online survey to evaluate our auditory displays from a larger sample size, which we hope will allow for this comparison.

To tally the BUZZ Scaled response scores, the negative feedback questions 7, 9, and 10 were converted to positive numbers "by subtracting the current numbers from eight" [22]. BUZZ questions 1, 2, 3, 8, and 9 were summed up for the "enjoyment and appeal" scale of the auditory display (35 points maximum), and questions 4, 5, 6, 7, 10 and 11 were added up to obtain the number representing the "ease of use" scale (42 points maximum). The maximum total BUZZ Scale response score is 77 points. We designated a 'fair' score equivalent to the sum of all eleven questions receiving "Do not agree nor disagree" scores (44 points total).

3.2. Data Analysis and Results

We calculated the mean and standard deviation of the BUZZ Scale results to assess the overall performance and iterative design process's effectiveness in enhancing the auditory display. The calculated metrics encompassed overall total scores that combined "ease of use" and "enjoyment and appeal" scores (Figures 2 - 4). The number at the center of the bar chart represents the BUZZ result value, while the error bars represent the standard deviation.

Based on the statistical data, we found nearly all auditory display BUZZ Scale compiled average scores were higher than a fair score in terms of both "ease of use" and "enjoyment and appeal" aspects, an indication that the overall design of all five auditory display prototypes was successful (Figures 3 and 4). We calculated Cronbach's alpha in our survey, resulting in 0.828, which indicated high consistency among each BUZZ question asked and thus high reliability in measuring the improvement from BUZZ scale results. The three displays where different versions were evaluated exhibited improvements in their total scores compared to previous design iterations (Long Term Axial Inflation Record, Net Flux of CO_2 Between Ocean and Atmosphere, and Daily Vertical Migration Gets Eclipsed).

4. DISCUSSION

Listening user tests are important [4]. Our approach favored incremental decisions and rapid testing of smaller groups. The iterative development of our listener-oriented segments and auditory display framework that contextualized each data sonification may account for some of the improvements in BUZZ Scale scores between versions (Table 3). For example, the Net Flux of CO_2 auditory display updates between testing sites included updating the display's overall scripted outline, adding an initial "hook" track to initially catch the listener's attention, adding music underneath the narrator for listener appeal, mastering the auditory display audio, updating the absorption sonification sound design, and adding start and end earcon wrappers around all sonifications. The 2015 Axial Seamount Eruption auditory display updates between sites included updates to script language, adding start and end earcon wrappers around all sonifications, remixing levels, and mastering the auditory display audio.

We have attempted to remain open to feedback throughout our project. For example, we updated the Net Flux of CO_2 absorption sonification's sound design after receiving strong reactions (both positive and negative) during workshop and conference presentations. Monthly meetings with the interdisciplinary team along with these varying types of feedback channels accelerated the iteration process.

5. CONCLUSION

Throughout the various rounds of feedback and user input, we uncovered a process and framework for developing and improving the auditory displays. Some of our process take-aways include:

a) develop learning objectives to guide sonification and narrative development;
b) build modular auditory display elements (sonifications, earcons, data narratives) to provide iterative production flexibility;
c) place earcons before and after sonifications to demarcate listening activities;
d) provide an auditory legend to enhance sense-making; and
e) include interdisciplinary representation from BLV, sound design, and learning sciences.

We found confirmation from BUZZ Scale responses that our auditory display designs that incorporate informative sonifications using authentic data were successful. The driving force behind the work has been the inclusion of all stakeholders and experts in the process. Next steps for our project include a large-scale online survey to further evaluate and support future work of auditory displays with informative sonifications within ILEs.

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