Multi-Modal Web-Based Dashboards for Geo-Located Real-Time Monitoring

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ABSTRACT

This paper describes ongoing research in the presentation of geo-located, real-time data using web-based audio and visualization technologies. Due to both the increase of devices and diversity of information being accumulated in real-time, there is a need for cohesive techniques to render this information in a useable and functional way for a variety of audiences. We situate *web-sonification*—sonification of web-based information using web-based technologies—as a particularly valuable avenue for display. When combined with visualizations, it can increase engagement and allow users to profit from the additional affordances of human hearing. This theme is developed in the description of two multi-modal dashboards designed for data in the context of the Internet of Things (IoT) and Smart Cities. In both cases, Web Audio provided the back-end for sonification, but a new API called DataToMusic (DTM) was used to make common sonification operations easier to implement. DTM provides a valuable framework for web-sonification and we highlight its use in the two dashboards. Following our description of the implementations, the dashboards are compared and evaluated, contributing to general conclusions on the use of web-audio for sonification, and suggestions for future dashboards.

1. INTRODUCTION

The number of Internet-connected devices continues to grow at an accelerated pace year after year. Examples of Internet of Things (IoT) devices include consumer products (such as smart watches, phones, and household appliances) and even critical infrastructure (such as traffic lights and industrial control systems). For the most part, the connected nature of these diverse information sources can contribute to greater efficiency and quality of life. However, managing and analyzing the data from these information sources effectively is challenging at scale and at near-real-time. The connected nature of these devices can also create unanticipated threats to security and privacy of a large populace. Thus, it is important to make the trends in device status and information available, and most importantly accessible to analysts, enabling them to monitor and affect changes in infrastructure.

In this paper we present methods for monitoring and exploring highly-dynamic, heterogeneous, real-time streams of information through web-based dashboards. We focus on geographically meaningful data: information related to a single major metropolitan area (Atlanta). Although this feature complicates dashboard representation in some ways, it also supports its representation in others. Our chosen applications include anthropocentric data, and the environmental, and technological aspects of smart cities—all reported through realtime IoT systems. Because this data can be extremely dense and multidimensional, it is difficult to effectively convey through visualization alone, and may need to be accessible, even when the user is attending to other tasks. Furthermore, we extend our target audience to the general public, making engagement and comprehensibility by non-specialists a cornerstone feature. By employing web-audio in our dashboards, a sonification layer can be added to the display, aiding in the presentation of the information, making the display more engaging, and offering benefits unique to hearing. Through our novel web-audio enhanced dashboard interfaces, our hope is that security researchers, smart city planners, and the general public will be able to effectively monitor and make sense of the complex spacio-temporal patterns about the state of geo-located areas, but also have an enjoyable experience that they wish to share with others.

The remainder of this paper is organized as follows. Section 2 provides background on the concept of sonification, introducing the benefits and limitations of desktop sonification environments and the possibilities for sonification using web-audio. A new application programming interface (API)—DataToMusic (DTM)—is discussed, which facilitated the application of web-audio for sonification purposes in the dashboards. Section 3 describes a dashboard application for monitoring the evolution of IoT devices in a geo-located area over time. Section 4 describes a second dashboard for exploring heterogeneous data from an urban environmental sensor array. After a discussion of how the DTM framework enabled the web-sonification designs in Section 5, the paper provides general conclusions, design guidelines and the prospects of future work.

2. BACKGROUND AND RELATED WORK

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2.1 Sonification

Sonification has existed as a field of research since at least 1992 [4], but documented instances of sonification extend much further in time [3]. The underlying theory of sonification is that in certain contexts, a data-driven auditory display will present advantages to visualization alone [8]. These include the fact that sonification does not require line-of-sight, allowing visual attention to be devoted elsewhere. Another benefit is that sound can provide an effective alert system, causing users to react faster than with the analogous visual information. The auditory system is also uniquely tailored to segregate multiple streams of information in parallel [2], which could be used to monitor and explore several layers of information simultaneously.

When envisioning how sonification might be useful on the web, these more 'scientific' advantages can be contrasted with the advantages of sound as a social, cultural, or otherwise *public* medium for information display [1]. In these cases, sound can be used to heighten the engagement with a data-display, leading to prolonged and repeated usage, as well as the desire to share the experience with others. It is important to note that creating strong and engaging experiences of data-driven sound are not necessarily incompatible with an objective and functional display, though certain guidelines should be considered [9]. Our dashboards sought to balance and highlight both specialist and non-specialist perspectives on the utility of sound for web-information display.

2.2 Limitations of Desktop Environments

In the recent history of sonification, the process of translation from data relations into perceived auditory relations has been accomplished primarily through desktop coding environments such as Max/MSP, Pure Data, and SuperCollider [3]. In general, these environments offer the greatest amount of flexibility for the creation and mapping of sound, but do not easily transport to mobile computing platforms or to the web. However, mobile computing and web applications are increasing in popularity and the new possibilities offered by these platforms are tremendous. If the field of sonification is to make use of the possibilities enabled by these web applications, it must adopt the new audio tools and technologies that have been developed therein.

For creating sonification applications that are accessible through the web, a developer is provided with roughly two options. In the first and most traditional use, a synthesis engine can be instantiated on a web-server, transforming a clients incoming data into audio, which can then be streamed back to a client. This choice however offers little possibility of interaction to the client, who may wish to change the data being sonified in near-realtime or explore an alternative mapping strategy.

In the second case, a developer may choose to use the Web Audio Javascript API.[1] The benefits of this option are that the synthesis and data selection process can occur on the client-side, enabling more possibilities for user interaction. In general, this allows a greater diversity of sonification strategies to be made available to the user. However, for a developer accustomed to the abstract and high-level synthesis available in desktop environments, the Web Audio API may seem opaque due to the low-level routing and connections the developer must navigate. The implementation of advanced synthesis techniques, musical structures, and having to learn a separate set of technologies for simply dealing with and manipulating the data source provide additional hurdles. For these reasons, we perceived the need to develop a new API which could lower the bar to web-sonification, making it easier for developers to create sonifications for their sites. Our API is called DataToMusic [6]. A brief summary of its affordances and programming structure are provided in Section 2.3, and later referenced in Sections 3 and 4.

[1]http://webaudio.github.io/web-audio-api/, Date Accessed: Oct. 15, 2015.

2.3 DataToMusic

The DataToMusic (DTM) API is a client-side JavaScript library for data handling, audio rendering, and other forms of musical output. It specializes in manipulating data at a symbolic level to create a sonification with complex musical structures [6]. However, it may be also utilized for various other sonification techniques, such as a conventional parameter modulation of a synthesizer, as it was developed to address the relative lack of general-purpose sonification tool sets for web applications. The DTM API consists of various modules such as dtm.array for encapsulating and transforming data sources, dtm.synth for audio rendering, dtm.guido for real-time score generation, and so on. In our dashboard applications, we utilize the dtm.synth object, which wraps the Web Audio API, to quickly load audio samples from the server and apply audio effects. The following example code is provided:

```
<code>
// Loads an audio file and plays asynchronously.
var oneshot = dtm.synth('percussion.wav').play();

// Apply parameter modulations and audio effects.
oneshot.pitch(2).attack(0.8).lpf(1200, 50).delay(0.3);
</code>
```

For each dashboard with varying data format and streaming rate, we utilize the data structure and transformation methods of DTM to align the data stream to the audio parameter mapping and musical playback.

```
<code>
// For a single value assignment
var v = dtm.array(data).range(0, 1).get('mean');

// For aligning the array length to the parameter
var seq = dtm.array(data).range(200,5000).fit(8);

dtm.synth().amp(v).freq(seq).play();
</code>
```

The Web Audio API provides a flexible audio graph system for dynamic patching of audio nodes. Its mode of operation can, however, sometimes mislead developers that audio nodes are destroyed and cannot be accessed through variables when a signal flow stops at certain point. To simplify the patching and re-patching process, the dtm.synth module provides a simple interface with chainable methods and internally manages instantiation or reuse of audio nodes. Besides for the audio synthesis, DTM uses the Web Audio

API for creating a sub-millisecond real-time callback clock that is used for scheduling audio events at musical and synchronized timing, as well as querying and mapping the data to the audio and visual parameters.

3. APPLICATION #1: IOT DASHBOARD

This dashboard was created as a result of new security vulnerabilities inherent to the Internet of Things (IoT). Shodan is a search engine that allows users to search banners of IPs—essentially the information about a system or device that is publicly available.[2] Although this access is not inherently a security vulnerability, banners expose information that can be used by hackers to breach their system. For example, a banner might expose that it is running Apache 2.1.3, an out-dated version with known security vulnerabilities. By searching Shodan for "Apache 2.1.3" this banner appears, and the device can be the target of an attack.

The Shodan Database is constantly crawling the web, finding new IPs, their open ports, geo-locations, and other publicly available information. The number of new IPs Shodan is able to find and post is staggering: up to 100 per second by informal estimation. Once a new IP is found, its information is put into a public database that is available on the Shodan website, or through the Shodan API.

One way to approach security is to first narrow focus to a particular geo-location (e.g. the U.S.A. or New York City), and search the database for known security vulnerabilities. While this method is useful, one also needs to have an eye (or ear) to the present to find new vulnerabilities as they appear in near real-time so that they might be dealt with promptly.

3.1 Sound Design

For this purpose, a process-monitoring web-sonification application was created for displaying new entries into the Shodan database. Process-monitoring is a common type of auditory display whereby a user can become aware of changes in a system while engaged in a secondary, parallel or otherwise more primary task [7]. Sound makes an ideal medium for this task as it does not require field of view or a user's direct attention to be perceived. However, sound is rarely used in isolation. In this application for example, sonification is combined with information visualization as well as interaction to allow the strengths of other perceptual and cognitive modalities to contribute to the utility of the application as a whole.

The sonification design consists of three simultaneous layers, from most general to most-specific: the sound environment, a constant tempo, and one-shot sounds. The sound-environment was created from a collection of eighty sound-files, organized into four environment categories (Beach, Rainforest, Storm, and Night) and two additional categories (foreground and background) [5]. The purpose of this layer of the sound design was to construct an overall impression of the current vulnerability level of the geo-location under investigation. For example, if there were overall few vulnerabilities in the system, the sound environment might play sounds of the "Beach" or "Nighttime." As potential vulnerabilities mounted, the sound environment might change to "Storm" or "Jungle," reflecting the need for higher vigilance and user input.

[2]https://www.shodan.io/, Date Accessed: Oct. 14, 2015.

The second layer of the sonification design was the use of tempo. Tempo was conveyed as a constant, un-accented pure-tone sinusoid with high temporal stability. A step-closer to the most direct level of one-shot sounds, tempo most closely corresponded to the general level of activity in the system. The more services that Shodan would find in a given time, the higher the tempo would become. As Shodan slowed in its rate of new services being found, the tempo would drop accordingly. For the purposes of stability, tempo transitions were a gradual process, and would occur slowly as the system would change. This higher stability over time contributed to the tempo being perceived as a background information stream. Dramatic changes in tempo over short segments of time would increase the perception of tempo irregularity and instability, which may become more distracting and annoying than desirable for a background information stream. A user can use this sound level to tune-in to the level of activity over time. For example, if a user were to step away from the monitoring task for a while and the return, tempo would give information that they might have missed. If the tempo were faster than when they left, then they would know that there had been significantly more activity than before. If the tempo were the same or lower, roughly the same number or less of entries would have been found.

The last level of the sonification design was the one-shot sounds, which were a collection of short, unique sounds of roughly equal loudness that would play upon the entry of new IPs. There would be a direct one-to-one relation of one-shots to entries, signaling new activity in the monitoring task. As not every entry has the same importance, and in general, it would be most advantageous to target IPs matching certain characteristics, the user may choose to map these one shots onto various search criteria, having a background less-salient stream of one-shots representing everything that does not match search criteria, and a second level of unique, highly diverse sounds that signal the appearance of matching keyword strings. Over time, a user can learn these one-shot mappings for search criteria. Furthermore, to increase the salience of matching one-shots, an echo effect might be applied, repeating the one-shot several times and increasing its temporal salience.

3.2 Visualization

In parallel to the sonification, a visualization and interaction scheme was created for exploring and gathering more information about the new IPs that had entered the Shodan Database. As the schema was to monitor new-entries for a particular geo-location, the primary display for the visualization was a map of the defined geo-location. When a new IP was found, a marker was placed on the geo-location of that IP. Because many IPs cluster on specific geo-locations, a technique for displaying these individual markers was implemented using the Spiderfy API for Leaflet.[3] For a collection of overlapping markers, this API serves to separate them out as a spiral, organized according to when they entered, with the most recent entries being closer to the center (see Fig. 1).

To assist the user in scanning large groups of markers for vulnerabilities, the markers were color-coded into 20 distinct color categories dependent upon the type of service

[3]https://github.com/jawj/OverlappingMarkerSpiderfier-Leaflet, Date Accessed: October 5, 2015.

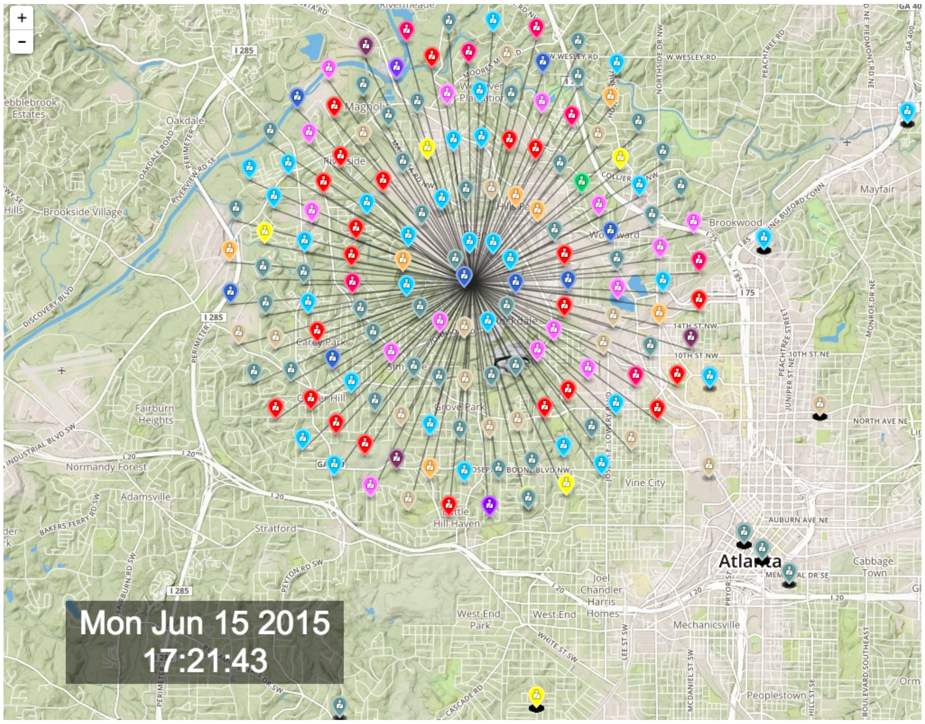

Figure 1: A figure showing the IoT dashboard using Shodan data. Each marker represents a geo-located service with color representing the type of service a device is running. Spirals are used to display many services with the same geo-location.

being run. For example, all IPS running an SSH server were color-coded red, TelNet servers were color-coded orange. The color mapping was applied to the 20 most commonly found services, and an additional color was used for all other services. In future versions, the user might be permitted to choose their own color mappings, or add more color mappings of their own choice.

Lastly, every marker could be clicked, revealing a text box with the banner as text. This assisted with rapidly scanning large amounts of banners, as they could be sampled without having to leave the dashboard itself. However, if a banner was deemed suspicious, or worthy of further investigation, a link back to the Shodan page for that IP was provided. This hyperlink served to provide the user with additional information available about the IP without having to create an entirely new framework on the dashboard itself. The Shodan page included other services and banners that were associated with that IP, and information such as the company when available. For HTTP/S links, the Shodan page also provided a means to go directly to that site.

3.3 Evaluation

The dashboard was demonstrated publicly at the Georgia Tech Research Institute Demo Day in June of 2015 to a group of professional security engineers. By wearing headphones, users were able to listen to the sonification and interact with the map-based visualization. The learning threshold was quite low, and little had to be explained regarding the interaction except that markers were clickable, and the map was zoomable. Users reacted favorably to the sound design, and seemed to understand the function and utility of the sound without explanation. The display was capable of engaging these users, even without expertise in the IoT. Further demonstrations of the strategy to professionals in the Array of Things project[4] was also favorable. Although having a sophisticated sensor and network infrastructure was important, the developers had realized that a cohesive framework for information communication and display was also valuable. To this end, the combined use of sound and visuals was favorable.

A movie demonstrating the IoT Dashboard in action is provided on YouTube.[5]

4. APPLICATION #2: SMART CITIES DASHBOARD

We created another prototype web dashboard to experiment with how raw sensor data can be processed, sonified, and visualized in order to make them accessible to end users. The end result—The Decatur Civic Dashboard—-is a networked sensor and web application system for a smart city analytics developed as part of the Civic Data Sonification project for the 2015 Atlanta Science Festival.[6] The interactive dashboard features real-time and historical data streaming of weather and environmental data, such as air quality, noisiness, various light intensities including infra-red and ultra-violet light, and several types of traffic data. In the real-time streaming, it receives 18 channels of such data

[4]https://arrayofthings.github.io/, Date Accessed: Oct. 15, 2015

[5]https://youtu.be/GoeOCLIghvM, Date Accessed: Oct. 15, 2015

[6]http://atlantasciencefestival.org/events/event/1095, Date Accessed: Oct. 15, 2015

from five sensor boxes. In the playback of historical data, user can specify the speed of playback (up to 20 times the normal speed). To stream various information in real time, we built custom sensor boxes using high-performance field programmable gate array (FPGA) and Raspberry Pi microelectronics with various environmental sensors and on-board processing algorithms. The dashboard provides user interface for filtering location and types of data, and visualization and sonification widgets that can be added dynamically. This dashboard offers a unique way of finding correlations of various human activities in multiple locations in real time with layers of visual and audio streams.

4.1 Sound Design

As with the IoT dashboard, sonification was fundamental to the interface design. The Decatur Civic Dashboard offers a customizable sonification widget with several distinct preset patterns. These presets utilize the musical instrument models provided by DTM API for creating expressions suitable for the dashboard's data streaming with relatively low rate but a large number of channels. The first preset is a pulsating instrument that conveys the motion of data with the density of the pulse. With the mapping toolbox, the user can assign any of the data sources to the speed of the pulse, which changes independently for each sensor box location. This layer of pulses, combined with the other mappings such as the timbre, pitch, panning, and dynamics creates a temporal expression with less sustain or overlaps that the user can perceive the overall speed or can focus on and track a single channel against the other channels. In contrast to the temporal instrument, another preset instrument is the slow-moving pad with continuously gliding pitch and amplitude. With this instrument, the user can sonify the contour of a data stream with harmonic effects. Besides the slower response of the parameter modulation, the user can set the window size for taking a short-term aggregate for any data. The third pattern is a one-shot instrument that is triggered at every data point, useful in the historic playback mode. These instruments can be used effectively when together by loading multiple sonification widgets and mapping different data sources to each parameter.

4.2 Visualization

By contrast to the IoT dashboard, the visualization component of the Decatur Civic Dashboard featured more traditional graphing strategies. The interface is displayed in Fig. 2. Using D3JS, continuous line-graphs and two bar charts widgets were made available to the user in five colors, representing 5 sensor box locations. The two bar graphs offer different views of the same data. In the upper bar graph, the bars are first grouped according to the various environmental data parameters, allowing a quick comparison between the sensor locations. In the second bar-graph, the sensor boxes are combined into one bar for each sensor parameter, essentially offering an overall magnitude estimation for that sensor parameter. Below the two bar-plots, a multi-line plot is used to illustrate the fluctuations in the data over recent time. At the top of the interface, the user is able to control "when" in time they are looking and at what speed they receive the playback, which can be used to review past data. The user can also enter realtime mode, where the speed is constant.

The visualization also shows where the sensor boxes are located on a map. As opposed to the IoT dashboard, the locations of data points in the Decatur Civic dashboard is fixed. By clicking on the markers on the map, the user can select which sensor locations they are analyzing or listening to. A movie demonstrating the Decatur Civic Dashboard in action is provided on YouTube.[7]

4.3 Evaluation

This dashboard was demonstrated to IoT researchers at the 2015 Discovery 2020 Workshop in Sante Fe, NM. It has since been evaluated by the multi-agency/university team leading the Array of Things project as an example user interface to the hundreds of sensor nodes planned for deployment in several major cities. The dashboard is currently posted online and will be evaluated using smart city infrastructure being deployed throughout the Atlanta metropolitan area.[8 9]

5. DISCUSSION

The mutli-modal dashboards described in Sections 3 and 4 provide demonstrations of how web dashboards can be designed to present the diverse array of information relevant to the IoT and Smart Cities. The use of web-audio in each case served to enhance the visualization—increasing engagement and allowing users to monitor many streams of parallel information while devoting their attention and visual field to other tasks. Multiple layers of sound served to alert users at multiple levels to the types of activity active in the system.

Specifically, the use of the DTM framework made the creation of musical structures using the Web Audio API much easier to implement, requiring much less code for the developer. The IoT Dashboard specifically made use of the tempo element that provides one of the DTMs most basic functions. Tempo is a valuable musical parameter for sonification that can be used to convey the amount of recent activity in a system and also be used to increase engagement of the display. Buffer handling was another major feature of the IoT dashboard, used for both playing environmental sounds and one-shots. The DTM also makes buffer handling, playback and manipulation much easier, which can be used for a variety of sonification type tasks.

The use of DTM in the Smart Cities Dashboard was more sophisticated, and in general this dashboard offered more possibilities for user control than present in the IoT. DTM in this case created more complex musical structures, and was even used to create a realtime music score. Although the creation of music is not necessarily the purpose of sonification, many techniques of sonification leverage musical tools and technologies. The DTM is an exemplary case of this technological convergence.

6. CONCLUSIONS AND FUTURE WORK

In this paper, web-audio was championed as a technology for the creation of multi-modal dashboards for the display of realtime geo-located data streams. By contrast to the current technologies for sonification—mostly Desktop oriented environments—web-audio offers a greater portability

[7] https://youtu.be/JwWNceoMqn8, Date Accessed: Oct. 15, 2015

[8] http://sonify.gatech.edu/, Date Accessed: Oct. 15, 2015

[9] http://smartcities.gatech.edu/, Date Accessed: Oct. 15, 2015

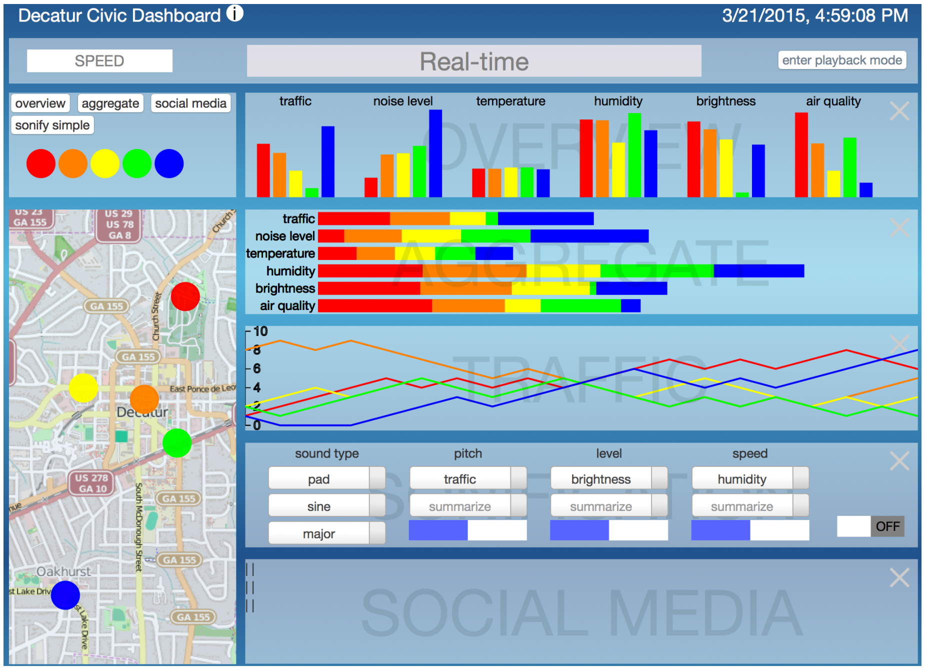

Figure 2: A figure displaying the Smart Cities dashboard. More detail is provided in Sec. 4.

and accessibility, leading in some cases to an expanded audience of end-users. By comparison, certain limitations of use of web-audio for sonification—including more difficulty for performing advanced synthesis, creating musical structures, and data handling—were made easier through the use of a specialty web-audio javascript library called DataToMusic (DTM). As DTM continues development and use in applications, the library will become stronger and even more useful for web-sonification.

The two dashboards presented offer a set of strategies for combining sonification with visualizations. When the data being presented refers to specific geo-locations, a designer is apt to implement a map with markers as part of the display. When the data features continuously changing data parameters, such as in the Smart Cities dashboard, a designer should use comprehensible graphing strategies offering a variety of views on the information.

Sonification designs should be used as a complement to the visualization, with the purpose of allowing monitoring of the system without giving visual attention. Alerts can be applied to provide information relevant to the user, but these should be balanced with a more general environmental soundscape, which can provide a more general sense of the system as a whole. Tempo and musical structures are useful parameters for increasing engagement with a display, functional for audiences of experts as well as the general public. The DTM is a valuable tool for web-sonification, which can help abstract web-audio for developers and provide them with a more useable framework for the implementation of sonification techniques.

In future work, we plan to continue developing web-based dashboards for the general public and specialists hoping to extract meaningful patterns from the data. We are continuing our work through the development of partnerships with interested groups. We hope that these examples can speak to the utility of web-audio for information display.

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