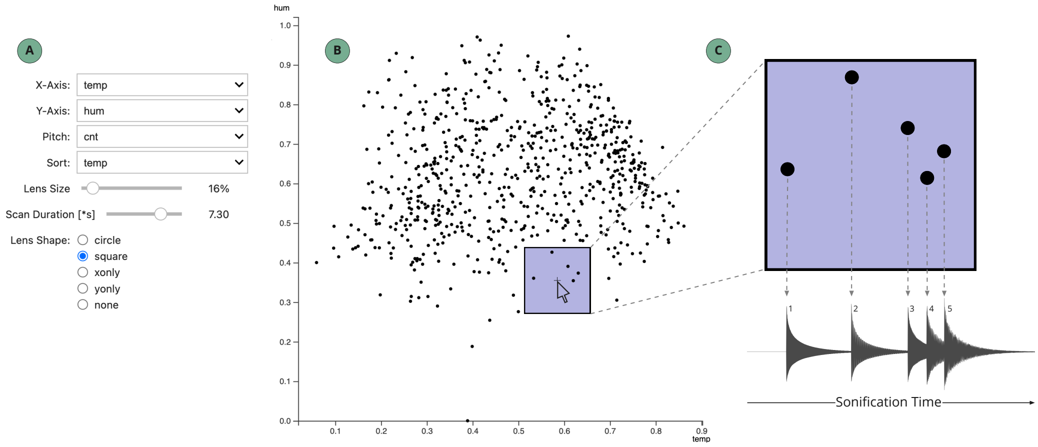
Towards Multimodal Exploratory Data Analysis: SoniScope as a Prototypical Implementation

K. Enge[1,2], A. Rind[1], M. Iber[1], R. Höldrich[2] and W. Aigner[1]

[1] St. Pölten University of Applied Sciences, Austria
[2]University of Music and Performing Arts Graz, Austria



X-Axis: temp
Y-Axis: hum
Pitch: cnt
Sort: temp
Lens Size 16%
Scan Duration [*s] 7.30
Lens Shape: ○ circle ● square ○ xonly ○ yonly ○ none

Figure 1: *Using the SoniScope approach to explore a "bike-sharing" data set. Section A: Users define visual and auditory mappings, the "Size" and "Shape" of the visual lens, as well as the "Scan Duration". Section B: Users specify an area in the scatterplot that will be sonified (Section C). A mouse click triggers the sound generation. While two of the selected attributes are represented visually in the scatterplot via abscissa and ordinate, a third data dimension (selected through the "Pitch" drop-down option) is mapped to the pitch of the sound events. The order of these events is determined by the "Sort" drop-down option. This example is also illustrated in the demo video.*

Abstract

The metaphor of auscultating with a stethoscope can be an inspiration to combine visualization and sonification for exploratory data analysis. This paper presents SoniScope, a multimodal approach and its prototypical implementation based on this metaphor. It combines a scatterplot with an interactive parameter mapping sonification, thereby conveying additional information about items that were selected with a visual lens. SoniScope explores several design options for the shape of its lens and the sorting of the selected items for subsequent sonification. Furthermore, the open-source prototype serves as a blueprint framework for how to combine D3.js visualization and SuperCollider sonification in the Jupyter notebook environment.

CCS Concepts

• ***Human-centered computing** → **Visualization systems and tools; Auditory feedback; Sound-based input / output;***

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1. Introduction

In exploratory settings, a human analyst generally searches for structures or patterns within data [Tuk77]. For example, scatterplots are often used for pattern-finding in two quantitative attributes. For exploring patterns in multivariate data, numerous visualization approaches have been proposed, such as a bubble plot with color, size, and shape channels, a scatterplot matrix, parallel coordinates, or a table lens [TS20]. Some approaches rely on interactivity or animation to explore attributes pairwise after each other [TS20], display overview and detailed data in multiple views [Rob07], or analytically reduce dimensionality [SMT13]. However, each of these approaches to the visualization of multivariate data has its limitations,

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such as small cluttered views, losing context by switching attention between different views, or non-relatable axes scales, which encumber analysts' working progress. Using other modalities, such as auditory perception, seems to be an opportunity to compensate for these limitations with the potential to reveal what otherwise would have been hidden in the data [MRB*18, MF95]. Two advantages of accompanying sonification are: (1) Visual focus does not need to be switched between multiple views avoiding loss of context, and (2) visualizations can remain less cluttered when parts of the data are represented via sonification.

In this contribution, we describe an approach to audio-visual data analysis inspired by the stethoscope, the tool of choice used by physicians for the auscultation of their patients' pulmonary and cardiovascular systems. During an examination, the physician places the stethoscope at different positions on a patient's torso and eventually asks them to breathe deeply or cough. The resulting acoustic sensation supports the identification of possible irregularities. Auscultation is a highly interactive and exploratory activity. Physicians rely on their experience and domain knowledge to convey their perception in an assessment of the patient's state of health. Relating to this routine, we designed SoniScope to enable users to explore multivariate data with their visual and auditory senses combined on equal terms. This is realized by displaying a 2D scatterplot and sonifying two additional attributes. The latter are represented by the pitch and the onset times of individual sounds, each representing one item within an interactive lens. With SoniScope, we developed a prototype that enables versatile implementations and evaluations of combined designs for future research. Conceptually, the approach is based on considerations of a combined design theory of visualization and sonification as outlined by Enge et al. [ERI*21] and is intended to support the evaluation of the theoretical constructs of the *substrate for sonification* and *auditory marks* that had adopted the corresponding terminology from visualization theory for sonification.

With SoniScope, we present (1) an approach for the combination of sonification and visualization for exploratory data analysis, (2) an open-source software framework combining Jupyter, D3.js, and SuperCollider, and (3) a prototypical implementation of the concept with a scatterplot and idiophonic sounds. Supplementary material can be downloaded at https://phaidra.fhstp.ac.at/view/o:4776 including a demo video and a demo Jupyter notebook.

2. Related Work

In visualization, the stethoscope metaphor has been adopted in the form of brushing interaction [BC87] and interactive lenses [BSP*93]. Brushed data items can, for example, be highlighted or filtered in multiple linked views [Rob07]. Alternatively, brushed items can remain highlighted while the view is rearranged to keep track of these items [YaKSJ07]. Under the interactive lens, the visualization is temporarily altered, e.g., to show more detail or a different arrangement [TGK*17]. SoniScope is different as it keeps the visualization unchanged and sonifies the demanded additional data.

While combinations of sonification and visualization exist both in general [RFJ*90, BHR05, Rön19], and with respect to accessibility for blind individuals [ZPSL08, RHR10, TKBH10, NG14], we focus on scatterplot sonifications in this section. Madhyastha and Reed [MR94] developed a sonic scatterplot representing visible dimensions redundantly via time and pitch. Flowers et al. [FBT97] designed an auditory scatterplot that enabled participants to estimate the magnitude of the correlation of two data dimensions as effectively as with a visual scatterplot. Crystallization Sonification [HR05] is a technique that enables users to browse high-dimensional data with a mouse via a scatterplot. The system provided information about the intrinsic (local) and the global data dimensionality, as well as about clusters. Also, Franchin et al. [FdLM09] implemented a Java web application for audio-visual data analysis using a shock wave metaphor in a scatterplot. Tünnermann et al. [TKBH10] developed a multi-touch desk interface allowing its users to excite high-dimensional sonification models. Their desk interface displays two data dimensions visually as a scatterplot and is able to sonify the other dimensions with the metaphor of a shock wave through a mass-spring system. Nees [Nee12] showed that visual and auditory scatterplots can be used equally well to explain the concept of correlation to students with no prior educational background in statistics, and Rönnberg and Johansson [RJ16] found that additional sonification supports users in distinguishing between different density areas in scatterplots. Their study participants needed more time to find dense areas but answered more accurately with the additional sonification. With the Interactive Mode Explorer, Yang et al. [YH18] implemented a tool that requires continuous interaction from its users: A scatterplot can be scratched over with a pen to sonify non-visible data dimensions. Recently, Patton and Levesque [PL19] presented *soni-py*, a Python package for sonification of a scatterplot without user interaction. While scatterplot sonifications usually map the spatial position of all point marks to sonification time [VH12] and pitch redundantly or use a (multidimensional) shock wave metaphor to sort auditory icons, SoniScope offers increased flexibility on two levels: Firstly, different lens sizes and shapes allow to select specific value regions in the data to be sonified. Secondly, different sorting and mapping options allow to explore a multivariate data set both in a complementary and a redundant manner.

Generally, in recent decades, both visualization and the sonification communities have gained interest in interactive multimodal interfaces. However, previous work often resulted in prototypes that address the research agenda of only one community. Despite a few examples of theory and implementation [Nes03, TKBH10], what is lacking is a basis for further development of multimodal approaches in both concept and software. While Enge et al. [ERI*21] discuss more theoretical considerations, this paper adds a software basis for the combination of sonification and visualization.

3. SoniScope as a Prototypical Implementation

The stethoscope metaphor and the auscultation method are adopted as a visual lens that is moved over a visualization, e.g., a scatterplot. SoniScope sonifies the items that are positioned under this lens using interactive parameter mapping sonification [HH11]. Thus, it supports users answering details-on-demand questions [Shn96] at an intermediate reading level [Ber83, p. 141].

For the acoustic impression of the individual items, we chose the sound of a mallet instrument like the marimbaphone: firstly, because it conveys a clear pitch, and secondly because it has a distinctly perceivable onset. Both qualities are essential for our sonification approach, using pitch and position in time as auditory channels. We designed the instrument using a resonator model and an impulse for excitation.

3.1. Functionality

With SoniScope (Figure 1), users are able to encode up to four quantitative data attributes into one audio-visual display. Two attributes are mapped to the horizontal and vertical positions of the point marks and two more attributes are mapped to the pitch and onset time of auditory marks, i.e. individual sounds [ERI*21]. An interface (Figure 1A) is available to prepare the tool for exploration and the visual display depicts all data items in a scatterplot (Figure 1B). At the present stage, the visualization uses only positional encoding as a minimum requirement for proof-of-concept. Additional channels such as color, size, and other encodings will be included in future versions. Brushing [BC87] over the scatterplot with a re-sizable lens enables the selection of a subset of items for subsequent sonification. The size of the lens can be changed with the mouse wheel while the lens itself can take several different shapes: *circular, square, xonly, yonly,* and *none*. The circular lens is designed to select items with a distance from the mouse position smaller than a set radius. The square shape is meant to select a Cartesian value region on both visual axes, while the two lens shapes xonly & yonly are used to select a slice or section of one visual dimension while sonifying the full range of values of the other. These shapes will be supplemented in future versions by rectangular and free-form shapes to allow even more specific brushing.

The sonification is started by a mouse click or touch gesture, triggering a temporally sorted playback of the items under the lens (Figure 1C). Which data attribute should be mapped to the pitch of the individual sounds is set with the *Pitch* drop-down option. Higher attribute values will result in higher pitches, i.e. the model uses a positive polarity between the data and the auditory sensation [WM10]. The playback order of the individual items can be set with the *Sort* option, and lower values in the selected attribute will lead to earlier start times of the respective sound. For this prototype, we decided not to implement animations like color or size changes at the times of the individual sounds, but want to investigate possible advantages of synchronized animation in our future work. The *Scan Duration* option changes the overall duration of the sonification. With a lens size of 100%, this value can be interpreted in seconds, i.e., with a value set to 3.6, the full sonification takes 3.6 seconds. Smaller lens sizes, therefore, lead to shorter overall sonification times, hence keeping the speed of the scanning constant for different lens sizes.

In addition to the basic visual and auditory mapping possibilities shown in Figure 1A, SoniScope offers a range of additional mapping settings that must be activated separately in the source code. A pitch range slider adapts the mapping between data values and pitch values to a chosen range. By default, the range is set from midi note 48 (C3) to 90 (F#6). A Euclidean distance option is available only for the circular lens and sorts the items according to their visual distance from the center of the circle. In this case, the circular shape of the lens is essential as the radius of a rising circle can be understood as a shock wave, simultaneously triggering items with the same distance to the center of the circle. That would not be possible with rectangular or square shapes. Without using the Euclidean distance option the individual sounds are sorted by the *Sort* option. Furthermore, an option is available that pre-processes statistical calculations and maps them to the decay, i.e. the duration, of the sounds. With this additional option enabled, a longer decay of the sonified items represents a bigger difference between the mean of the lens data and the overall mean, both with respect to the *pitch* attribute. By default, individual auditory marks have a decay of one second. They are slightly panned in the stereo field depending on their visual horizontal position.

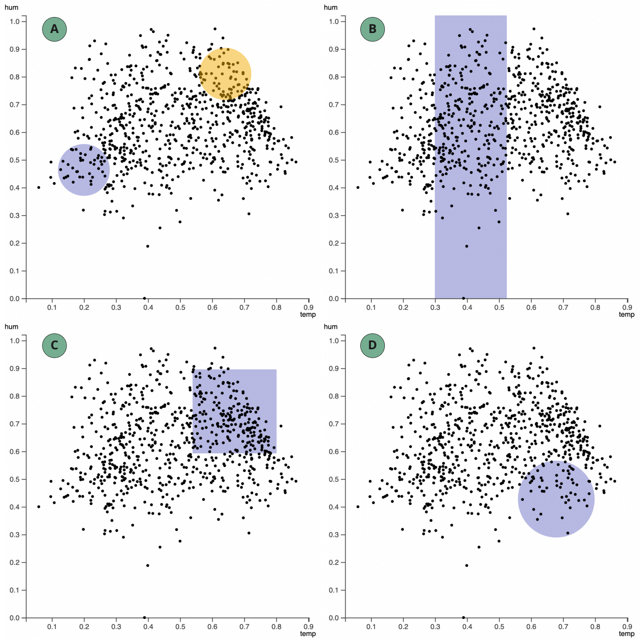

Figure 2: *Different lens shapes and sortings can result in different characteristic auditory patterns. (A) The comparison of two regions by clicking one after the other. (B) Scanning the data from left to right, revealing a correlation between visual and auditory dimensions. (C) Using the same attribute for the pitch and the sorting dimension reveals special data distributions. (D) A region with long decay could be a group of outliers. These four situations are also discussed in the demo video.*

3.2. Usage Scenario

As an example data set, we used the “bike-sharing data set” from the UCI Machine Learning Repository [DG17, FG13]. The data set provides daily bike-sharing information from Washington, DC, from the years 2011 and 2012 and consists of 731 items with 16 attributes like normalized temperature, normalized humidity, and the total number of rented bikes for each of the 731 days. Since the weather measurements are stored normalized in the data source, they are also displayed with axis labels between 0 and 1 in the figures.

Different combinations of audio-visual mappings can reveal different structures within the data. Figure 2 and the demo video indicate some of the possible exploration settings: (A) shows how two regions can be compared to each other by clicking first in one and then in another. If the attribute mapped to *pitch* differs in these regions, the user will hear, for example, one higher and one lower sounding pattern. In (B), the *xonly* lens is used to scan the selection from left to right, exciting the individual items in their visible order. Such a redundant mapping of one single attribute to both the visualization and the sonification can reveal a correlation between the abscissa attribute and the *pitch* attribute. A positive correlation would result in an auditory sequence with rising pitch. Within the bike data set, for instance, a user would find the expected correlation between temperature and the number of rented bikes, as the pitch of the selected item tends to rise with higher temperatures.

Another possibility is to map one attribute to both pitch and the sorting dimension. This can be done with the square-shaped lens like in (C) but also with any shape. Such a mapping will result in the perception of a sweep, which is easy to recognize and could inform users about missing values or unexpected data distributions. With the decay mapping option enabled, SoniScope conveys information about the relation between the overall mean value of the selected attribute and its mean value within the lens region. If the mean of the lens region in (D) differs from the overall mean, then the individual sounds will have a longer decay (up to 10 seconds). For the given example of the attribute *number of bikes* in the bike data set this results in quickly decaying sounds, when the overall mean and the mean of the selected region are similar. In the demo video, this is the case for the upper right area of the scatterplot.

3.3. Software Framework

For the implementation of the SoniScope approach, we devised a software framework that combines visualization and sonification on equal terms and that, at the same time, allows for a high degree of interactivity. This framework needs to be extensible to allow experiments with alternative visualization or sonification approaches and the installation procedure should also be as simple as possible.

The visual aspects of the SoniScope implementation are displayed in the web browser using visualization components of D3js.org. In contrast to a grammar-based visualization libraries such as Altair [VGH*18], this approach allows for fine-grained control of interactivity and bringing any bespoke D3.js visualization under the SoniScope lens. For the auditory aspects, the browser-based Web Audio API is not yet widely adopted for non-trivial sonifications. Therefore, we chose SuperCollider (supercollider.github.io), a platform for audio synthesis that is popular within the sonification community for its real-time synthesis capabilities. Our framework joins these aspects on the platform of Jupyter.org notebooks, which is widely used in data science. Figure 3 illustrates how SoniScope is positioned in a Jupyter notebook document that is displayed in the web browser and backed by a Python kernel. Data is loaded via the pandas library and passed on to the SoniScope widget within the Python kernel. Using the Jupyter widget API, slices of the data are synchronized with the widget view component that runs in the web browser, while the amount of data synchronization is reduced to a minimum. A pointer event in the widget view is sent to the widget in the Python backend, where the data is filtered based on the lens' position, shape, and size. These filtered data are sent to the SuperCollider server via sc3nb [HR21] to be sonified.

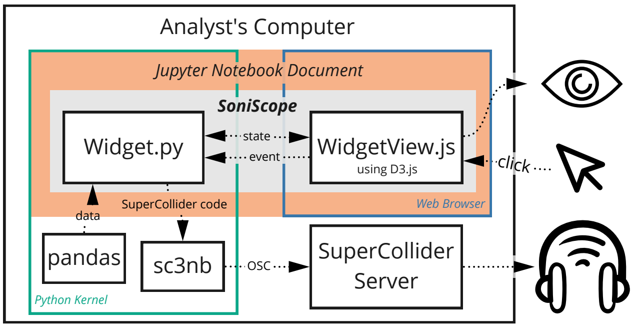

Figure 3: *The software framework of SoniScope, combining a D3.js visualization and a SuperCollider sonification in Jupyter.*

4. Conclusion

At the present stage, SoniScope demonstrates what we envision as a theory-based data analysis approach that combines visualization and sonification on equal terms. Analysts can use the described functionality. Developers of both disciplines can use it as a starting point to design refined visual and auditory representations and experiment with the resulting multimodal display. Eventually, SoniScope will serve as an example application to support an approach towards a combined design theory on audio-visual data analysis.

In particular, we anticipate four paths for future work: First, the sonification will be extended to more sophisticated parametric models [Her11] for multivariate data representation. This will demand more advanced synthesis techniques, such as granular or concatenative synthesis. Likewise, the visualization refinements such as heatmaps or scatterplot matrices can scale to a larger number of items respectively attributes displayed. Second, the tool now combines 0D visual marks, points in a scatterplot, with 0D auditory marks, i.e. their individual evolution over sonification time does not directly represent a data dimension [ERI*21]. Going forward, 1D visual marks such as lines in parallel coordinates and 1D auditory marks, i.e. sounds representing an item along a sorted attribute by their temporal evolution [ERI*21] are feasible within SoniScope. Third, extending the statistical, relational, and derivative pre-processing functionalities will strengthen cross-modal aspects between the visualization and sonification. Finally, we intend to integrate the SoniScope lens with its customizable sonification into visualization grammars such as Altair [VGH*18] to offer even more rapid prototyping.

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