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as of 01-Jul-2019

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Major Goals: The goal of this project was to develop a prototype dynamic tool that enables exploration of connectome network data in a 3D interactive video game environment (using the UNITY gaming engine). We have drawn on and expanded existing taxonomies of data sonification to allow multiple ways of sonifying the same data to draw attention to different aspects of that data. The software embodies the concept of 'Data Stethoscopes', or developing data exploration tools that exploit human ability to compare and contrast two sounds. Collaboration researchers at the UT Dallas Cognitive Neuroimaging Laboratory and the ArtSciLab have tested a number of modules to examine sonic differences in brain network organization; the data used allowed comparison of functional magnetic resonance imaging (fMRI) data of individuals of different ages, an area where the PI has published results that can be tested and compared with the sonification tool. The research methodology was based on a transdisciplinary collaboration between artists and scientists who jointly developed the tools for testing. To demonstrate extension to other types of data, the tools were successfully applied to a connectivity dataset obtained using intracranial electroencephalography recordings of human patients. While initial results are promising, interim results indicate that further work is needed in order to utilize the tools in a formal research setting. In addition, the tools and data were used in an artistic performance. The art performance was in Seattle October 2017 as part of the re-staging of the Nine Evenings performance originally carried out in 1967 between Bell labs engineers and NY artists. The second performance was held at the University of Caldas during the International Symposium of Electronic Arts. The successful results of this initial phase which was funded by DARPA has established the basis for a subsequent phase of development involving developing a Data Stethoscope Training module for user experience testing and data analytics testing

Accomplishments: 1. Development of network sonification and 3-dimensional (3D) interactive visualization software

The major result of the work on this project was that an extensive extensible software code base was created. This work created multiple sets of visuals (based in Unity) that allowed active exploration and interaction by the user to within a 3D model of the brain. The user is able to navigate around and through the neural bundles and systems that neuroscientists use to compare systems. The user was given access via a gaming style interface to "fly around" in the model and activate the interconnections between the various brain systems. Not only do those systems light up with animations that show the nature of the strength of specific interconnections that are triggered, but these triggers are accompanied by information rich sounds sonifications that allows exploration of these complex (brain) networks in unique experiential ways. Using the interface of artistry and scientific knowledge a unique new way for users to interactively discover the relationship of links within and between systems was made sensorially apparent.

By enabling the user to choose not only position in the model but the look and feel of the model itself, an immersion

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into what was before only rows and columns of numbers of an Excel sheet becomes an immersive experience. The more familiarity users have with the model the greater the extent of the discovery potential. Users also choose which of many algorithmically driven sound interactions they experience. This means that the consequence of specific triggering interaction creates cascades of sound that are the direct result of the user's specific interaction. It should be noted that the engine was fully supportive of modern VR headset technologies and designed to further explore the potential that these burgeoning new technologies present.

2. Developed and tested taxonomies of sonification.

- a. We learned that most of our early sonification were looking at the relatively small number of strong linkages to individual nodal clusters, which our system was well-equipped to handle, but, counter intuitively, we discovered sonification appears to be most useful to experience patterns across large numbers of nodes and linkages in the brain and situations where data density and complexity makes comprehension of graphic presentations difficult.
- b. The creation of a new extension of a sonification taxonomy that isolates distinct approaches of both classification and technique in the area of converting data into informatic sound was a major and important result of this project. Here are some examples:
 - i. We developed as a result of these distinctions techniques that played the proximity between network clusters as a harmonic spectrum with overtone series. The data used indicated the internal connections within the cluster and if the connection itself was even within the system itself. If outside of the system the connection was represented by higher and higher overtones that naturally let the user hear the strength of the connection was diminishing even if the physical location of the neurons being compared was proximate.
 - ii. We developed as a result of these distinctions techniques that played the entire data set as a "soundscape" that allowed the users to explore the interrelationships between the clusters of neurons representing within, without and at the boundaries of distinct neurological systems. These soundscapes would discernibly change with data sets from various age groups. This lead us to two modes exploratory and what we called the "roller coaster" technique, where individuals were guided on pathways that had been previously identified.

3. Conceptual and Methodological Results

- a. We developed software that allowed exploration of complex network data
- b. We demonstrated that two datasets could be differentiated solely from data sonification. We were able to establish that two fMRI data sets (e.g., data from two different age cohorts) could be compared sonically, and after some acclimation the user was able to correctly identify which age cohort was being represented heard with a given tool. (see Appendix 3 for video abstract)
- c. We confirmed that data sonification user require auditory training. We discovered that the aspect of "training" with each of the new techniques that we introduced definitely improved the efficacy of the sonification being used. This has led to our ongoing research to always have a Learning, Exploring and Testing component. We discovered the manual controls of knobs and sliders to change specific parameters sometimes had an advantage over screen based interaction in controlling interactive and dynamic audio visual system parameters. We also found that we needed to build in more flexibility for sonification and analysis plugins to specify user interface affordances in the visual server tailored to their several individual requirements. This would also include compensation for hearing loss and diminished spatial perception. We also discovered the value of providing adjustments available to users of the system to tune the particular sonic appearance of sonifications. It was difficult for the sound designers to plan in advance what particular sonic properties would be intelligible and pleasing to scientific users, and giving the users the ability to fine-tune the sonifications to their personal taste increased their value and intelligibility. One result made in this current research is the benefit of offering a variety of (more than one) approaches to examining the data set. Using various types and technical approaches to sonification have yielded a clarity of interpretation of the data not as readily apparent with just a single technique.
- d. Multiple technical developments resulted (scripts, code, software etc.) We developed and tested how physical interfaces added value beyond screen based interfaces. Please see the attached addendum for more specific representations of the technical developments and software that was developed for our testing and use during this project

4. Insight about musician-scientist collaboration.

The work was a case study demonstration how art science collaboration can result in novel insight. We demonstrated that an art science collaboration could lead to novel approaches, and tools; for instance, a "drumming" gestural interface to the fMRI data was used in performances and could be adapted for use by researchers. Novel tools were designed driven by the art performance context, some of which could be transferred to scientific use.

5. Performance Results

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Data Stethoscope for the Brain Connectome / Oct 28, 2016 for the 9E2 event at the King St. Station in Seattle. A project involving the Data Stethoscope project at UTDallas was asked to “perform” with a multimodal research tool set for examining complex networks derived from fMRI data. 9e2 was an art exhibition and performance series in Seattle commemorating “9 Evenings: Theatre & Engineering”, an iconic exhibition 50 years ago in New York that sparked a new era of collaboration between artists, scientists, and engineers”. This project represents the ongoing research investigating new techniques for not only representing data as visual images, but also accompanying those visual images with sound realizations of the data. This paper describes aspects of the processes involved in the three unique interpretations of data that were presented in performance at the 9E2 event in Seattle that evening. The performance of the software and data developed for this project is part of a research methodology that involves art, design and humanities methods as part of the scientific method used.

Training Opportunities: Working closely with PhD and Master's Degree candidates to help integrate the various aspects of the development of this work. Since it was an integration of Gaming and VR engine technology and the use contemporary techniques computer music generation. Specifically, an extensive visual environment in the Unity game engine and using the open source software programming language Pure Data was shared with various graduate students working on parts of this project. One of these graduate trainees have gone on to take a position in industry (e.g., currently employed at Mathworks), another is presently a post-doctoral trainee at UTD, while a research assistant is currently an MD/PHD student at Yale University.

Results Dissemination: There were two contexts where the results of this research were presented to the public in artistic performances, which also led to public dialog and further and more far reaching developments in the general area of sonification.

1. The first, primary, performance was in honor of the celebration of the 50th anniversary of the Nine Evening performances in 1966 where prominent artists and Bell Labs engineers performed in public in New York. The performance used both the data and the software developed for a data stethoscope project that is associated with ongoing research with a team of Neuroscientists at the Center for Vital Longevity Studies at UTDallas. The project data was fMRI data on age cohorts of healthy individuals from 20 to 80. The research involved adding sonification to visualization tools as a strategy for data exploration. For example, in one piece the artist (Scot Gresham-Lancaster) developed an interface and performance strategy with a chess board and various midi controllers. Two of the scientists (Gagan Wig and Roger Malina) played chess which controlled the presentation. Using various data sets from the research a soundscape and real time interventions based on the “Reunion” electro-acoustically enhanced chess match between Cage and Marcel Duchamp from 1968. In this case, the two collaborating scientists play chess on an electronically enhanced chess board. The moves they make drove the soundscape and interaction of both the video and audio of the performance. The interactions were enhanced by actions and reactions during the performance. Portions of this performance can be viewed here:

<https://vimeo.com/216085736>

In the context of the 9E2 event at the King St. Station in Seattle in October of 2016 we worked closely with many other new media and sound artists working at this union between consumer and gaming product development and new media art practice. This in turn lead to several interviews and discussions on the publicly accessible “Sound and Data” channel on the “Creative Disturbance” Art Science aggregate.

2. A second similar performance was conducted at inauguration of the new Bank of the Republic public exhibition space (Inauguración Banco de la República) in downtown Manizales, Columbia. Details here:

<https://festivaldelaimagenisea2017.sched.com/event/Ah8w/soundscapes-reunion-2-performance-of-the-data-stethoscope-for-complex-networks-of-fmri-data-and-chess-board>

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: All developed software has been transferred to DARPA

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Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

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Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Faculty

Participant: Scot Gresham-Lancaster

Person Months Worked: 2.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Other Professional

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Person Months Worked: 2.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

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Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

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International Travel:

National Academy Member: N

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National Academy Member: N

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Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Co PD/PI

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Person Months Worked: 1.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Other Professional

Participant: Mike Leach

Person Months Worked: 3.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Other Professional

Participant: Robert Naly

Person Months Worked: 3.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

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as of 01-Jul-2019

DARPA Final Progress Report - Data Stethoscope For the Brain Connectome

Report Date: April 26, 2019

Final Progress Report

July 31 2016 to September 31 2016

Report Title: Data Stethoscope For the Brain Connectome Final Report

Grant Number: Grant 67905-LS-DRP, Agreement: W911NF-15-1-0475

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(1) Forward

We have developed a prototype dynamic tool that enables exploration of connectome network data in a 3D interactive video game environment (using the UNITY gaming engine). We have drawn on and expanded existing taxonomies of data sonification to allow multiple ways of sonifying the same data to draw attention to different aspects of that data. The software embodies the concept of 'Data Stethoscopes', or developing data exploration tools that exploit human ability to compare and contrast two sounds. Collaboration researchers at the UT Dallas Cognitive Neuroimaging Laboratory and the ArtSciLab have tested a number of modules to examine sonic differences in brain network organization; the data used allowed comparison of functional magnetic resonance imaging (fMRI) data of individuals of different ages, an area where the PI has published results that can be tested and compared with the sonification tool. The research methodology was based on a transdisciplinary collaboration between artists and scientists who jointly developed the tools for testing. To demonstrate extension to other types of data, the tools were successfully applied to a connectivity dataset obtained using intracranial electroencephalography recordings of human patients. While initial results are promising, interim results indicate that further work is needed in order to utilize the tools in a formal research setting. In addition, the tools and data were used in an artistic performance. The art performance was in Seattle October 2017 as part of the re-staging of the Nine Evenings performance originally carried out in 1967 between Bell labs engineers and NY artists. The second performance was held at the University of Caldas during the International Symposium of Electronic Arts. The successful results of this initial phase which was funded by DARPA has established the basis for a subsequent phase of development involving developing a Data Stethoscope Training module for user experience testing and data analytics testing

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8. Research Review of Taxonomies for Sonification

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- 2) Technical Report: Sonification Categories
- 3) Access to “Screenshots of Data Stethoscope Tool”
- 4) Access to “Data Stethoscope Demonstration Videos”
- 5) Data Stethoscope 9E2 Performance Document
- 6) DATA Stethoscope Project - Technical Note No 2

(4) Statement of the problem studied:

New challenges are being posed by large complex data sets that require pushing beyond current data visualization approaches. Sophisticated interactive mathematical and data visualisation tools are beginning to allow us to mine the complexity of this information to reveal important patterns in the data. Critically, inherent capacity limits in perception and attention often limit our ability to easily discover and to communicate aspects of information that are not readily revealed by solely visualizing data. The hurdles in effective analysis are not limited to that between specialists and non-specialists, but also prevent clear knowledge transfer between trained and informed experts within a given domain. From our previous research and planning for this project, we decided to integrate both the visual representation of the 3d model of the complex network that represented fMRI data under study and to additionally sonify that data in synchronization. This goal had some inherent hurdles since none of the tools to accomplish this existed and needed to be designed, built , tested and rebuilt over many iterations.

The framework of our design approach included the need to create tools that could be functional in the lab as well as in a performance context. To accomplish our goals we decided to work with contemporary gaming and computer music technology using the Unity game engine, Pure Data real-time graphical programming environment for audio, video, and graphical processing and communicating between these two powerful applications using OSC Open Sound Control a protocol for networking sound synthesizers, computers, and other multimedia devices. The intent of this approach was to leverage the strengths of the disciplines of game design and computer music creation to solving data analytic research problems that are confronted in modern neuroscience research.

(5) Methods

In this project we drew and expanded on prior research in audio display and sonification of data. We developed new tools, involving both visualisation (developed in a 3d video game environment; UNITY) and sonification . The tools were tested on brain connectome data (measured using functional magnetic resonance imaging [fMRI]) currently being collected and analysed by the PI. In addition, a second data set provided by DARPA (a brain data set collected using intracranial electroencephalography (iEEG) recordings of human patients, from researchers at Massachusetts General Hospital) was examined using the tool.

One key problem is the lack of standard sonification methods used by researchers, as is the case in data visualisation. We therefore developed a Sonification Taxonomy (S. Gresham Lancaster et al., 2016 included as Appendix 2). We developed a strategy of sonifying the same data using different categories of sonification in the Taxonomy; this allowed us to examine whether a user could distinguish a given aspect of data using different categories of sound.

Given that the data we were working with was based on complex network analysis, not all of the sonification approaches we have identified in the more global taxonomy were appropriate. Much of the investigation was indeed spending time identifying sonification types and techniques that were found to have more efficacy by the neuroscience team. Ultimately we found that several types of sonification classifications were effective in isolating specific problems. We ended up isolating 6 of these 9 techniques as:

1. Data as gestalt -the discrete representation of the data. Individual data “packets” or icons of sound shaped by the scaled data - raw sound buffers, waves from time series data
2. Data as melody or harmonic movement - the “Musification” of data units as notes
3. Data as gesture -Data as gesture - a sea of sequences that are experienced as a sound field, motion driven, loops of fixed data or data driven processes
4. Data as location: familiar or biological signals and audio material distributed as a 3d field and displaced by location and reverb (sound mapping (real world and virtual))
5. Data as environment - Mixing the abstract electroacoustic space with a mixing board, combining and mixing levels with a midi controller
6. Data as presence - the combination of sound possibilities driven by interaction and navigation - (Data Forest)
7. Data as music construction - Fragments of data set are combined horizontally and vertically eg Tunification like Musification (2) but with composerly intervention
8. Data as extrinsic: parameter change - freq., pitch, tone, reverb driven directly by data dimensional vectors.
9. Data as anomaly: enigmatic sonic configurations that make the familiar, unfamiliar. Playing music or familiar speech (podcast) through various parameterized digital signal processing (resonate filter, delay, reverb etc.) (refer to Exformation)

A more detailed explanation of the meaning of each of these is found in the Appendix 2 and 6, but relevant to the actual work that ended up having the most efficacy for the particular problems of the aging of the brain and the connection inside and outside of specific brain systems, we ended staying pretty focused on the use of harmonic listening (#2). A conclusion that can be reached from our experience is that more research is needed to isolate whether this efficacy was based on the familiarity of the users with thinking of sound in terms of and familiarity with harmonic content. Further investigation that integrates training of users into the process of gleaning information of sounds has been the focused of our current research.

In addition, different visualizations were created, but this was mainly done for aesthetic purposes (which also served the data performance goals).

The focus of the work was centered on data generated from the proposal PI’s (GW) research program that is aimed at understanding how patterns of brain connections, measured using fMRI

in humans, differ and change across the adult lifespan in both health and disease. Accordingly, the ‘model’ dataset (a large dataset of functional brain connectivity data obtained from healthy adults; n=210; age-range 20-89 years; initial observations published by Dr. Wig’s group using this data: Chan et al., PNAS, 2014) has afforded the group the opportunity to consider a number of aspects of data representation, as brain connectivity information is inherently: (1) complex, (2) dynamic, and (3) interesting to a diverse audience. We successfully leveraged this type of data to build a multi-modal 3D interactive tool that enabled data exploration in an unprecedented manner.

Performance Methods. Regarding the new methods organizing a performance with these tools, once it became clear that the geographic dislocation of the three participants ruled out the ability for there to be real time dynamic network interaction between the players, the topography and sequence of the work was rearranged. This serendipitously resulted in an exhibition performance that highlighted three very distinct approaches to using the same set of data for three very different types of performance. This ended up accentuating the differences in perspective shared by all the performer/composers. The performance opened with a percussion interface where the nodes were “struck” and the links to the struck node sounded. Second, was an interface that could be dynamically triggered by the performed using the specific qualities of the model with custom sounds that represented the interaction. Finally, an electronic chess board drove the navigation through the actual tool and the resulting sound were an exploration of that interface. See Appendix 5 for a more detailed account of these new methods and techniques.

The results of our initial work in this area were not conclusive. There are many factors that contribute to understanding and deployment of sonification techniques since these techniques are not fully integrated in the workflows in modern neuroscience lab practices. To that end and beyond the end of this initial study we have continued to work with the class of interactive and ubiquitous Jupyter notebooks. Our intention with this strategy is to use tools more fully integrated in the workflow of not only neuroscience labs but data analytics practices across across many scientific disciplines. More research is needed to isolate effective techniques and determine means of distribution of those procedures once they are tested for efficacy.

(6) Summary of the most important results:

1. Developed and tested of taxonomies of sonification (taxonomy, different sonifications used/ones that worked etc)
 - a. We learned that most of our early sonification were looking at the relatively small number of strong linkages to individual nodal clusters, which our system was well-equipped to handle, but, counter intuitively, we discovered sonification appears to be most useful to experience patterns across large numbers of nodes

and linkages in the brain and situations where data density and complexity makes comprehension of graphic presentations difficult.

- b. The creation of a new extension of a sonification taxonomy that isolates distinct approaches of both classification and technique in the area of converting data into informatic sound was a major and important result of this project. Here are some examples:
 - i. *We developed as a result of these distinctions techniques that played the proximity between network clusters as a harmonic spectrum with overtone series. The data used indicated the internal connections within the cluster and if the connection itself was even within the system itself. If outside of the system the connection was represented by higher and higher overtones that naturally let the user hear the strength of the connection was diminishing even if the physical location of the neurons being compared was proximate.*
 - ii. *We developed as a result of these distinctions techniques that played the entire data set as a “soundscape” that allowed the users to explore the interrelationships between the clusters of neurons representing within, without and at the boundaries of distinct neurological systems. These soundscapes would discernibly change with data sets from various age groups. This lead us to two modes exploratory and what we called the “roller coaster” technique, where individuals were guided on pathways that had been previously identified.*
2. Methodological Results
- We demonstrated that two datasets could be differentiated solely from data sonification (exploration/understanding results (points about comparing fmri and other data sets)
 - We were able to establish that two fMRI data sets (e.g., data from two different age cohorts) could be compared sonically, and after some acclimation the user was able to correctly identify which age cohort was being represented heard with a given tool. (see Appendix 3 for video abstract)
 - Many technical development resulted (scripts, code, etc etc) We developed tested physical interfaces added value beyond screen based interfaces. We confirmed that users must be trained carefully to distinguish different sounds, of different categories in the taxonomy. Existing literature on the use of medical stethoscopes has established this requirement, and we confirm it is needed for data sonification. We also observed that the musicians on our team were more successful at differentiation of the sonifications than the team members with no musical background.
 - Collaboration results (musicians-scientists) The work was a case study demonstration how art science collaboration can result in novel insight.

We demonstrated that an art science collaboration could lead to novel approaches, and tools; for instance a “drumming” gestural interface to the fMRI data was used in performances and could be adapted for use by researchers. Novel tools were designed driven by the art performance context, some of which could be transferred to scientific use.

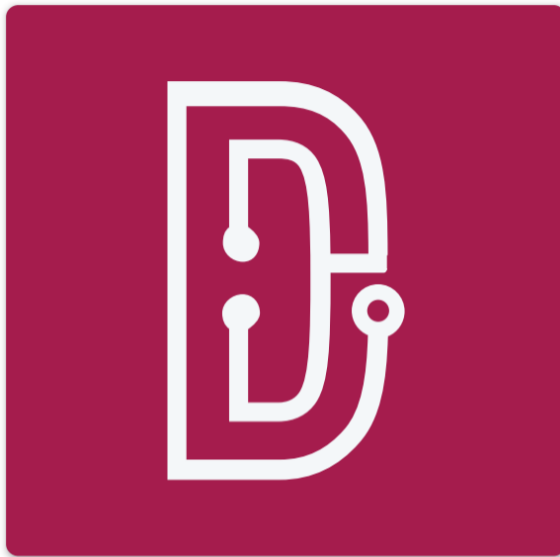
- We confirmed that data sonification user require auditory training. Experience results (knob controls, training, musicians vs others etc) We discovered that the aspect of “training” with each of the new techniques that we introduced definitely improved the efficacy of the sonification being used. This has lead to our ongoing research to always have a Learning, Exploring and Testing component. We discovered the manual controls of knobs and sliders to change specific parameters sometimes had an advantage over screen based interaction in controlling interactive and dynamic audio visual system parameters. We also found that we needed to build in more flexibility for sonification and analysis plugins to specify user interface affordances in the visual server tailored to their several individual requirements. This would also include compensation for hearing loss and diminished spatial perception. We also discovered the value of providing adjustments available to users of the system to tune the particular sonic appearance of sonifications. It was difficult for the sound designers to plan in advance what particular sonic properties would be intelligible and pleasing to scientific users, and giving the users the ability to fine-tune the sonifications to their personal taste increased their value and intelligibility.
- One result made in this current research is the benefit of offering a variety of (more than one) approaches to examining the data set. Using various types and technical approaches to sonification have yielded a clarity of interpretation of the data not as readily apparent with just a single technique.
- Related to the point above, when we tried to build more complex sonifications based on larger sets of data, studying system-wide linkages and change with age across multiple subjects, we found that we needed to have a more carefully engineered and optimized system of data access, to give flexible and fast loading and representation of the millions of data points collected in our underlying studies. This problem was particularly challenging for data visualization using Unity; the tool in its current form was unable to visualize a large number of continuously changing

connections (e.g., >40,000) and was constrained by this. We overcame this limitation by creating sparser network graphs when visualizing each individual's network (i.e., changing across 210 networks), and by limiting the number of changes to 2-3 networks if denser networks were being visualized.

3. Performance: Data Stethoscope for the Brain Connectome / Oct 28, 2016 for the 9E2 event at the King St. Station in Seattle. A project involving the Data Stethoscope project at UTDallas was asked to “perform” with a multimodal research tool set for examining complex networks derived from fMRI data. 9e2 was an art exhibition and performance series in Seattle commemorating “9 Evenings: Theatre & Engineering”, an iconic exhibition 50 years ago in New York that sparked a new era of collaboration between artists, scientists, and engineers”. This project represents the ongoing research investigating new techniques for not only representing data as visual images, but also accompanying those visual images with sound realizations of the data. This paper describes aspects of the the processes involved in the three unique interpretations of data that were presented in performance at the 9E2 event in Seattle that evening. The performance of the software and data developed for this project is part of a research methodology that involves art, design and humanities methods as part of the scientific method used. Please see the Appendix for a full paper of the performance and it's outcomes

Summary of tools/procedures developed.

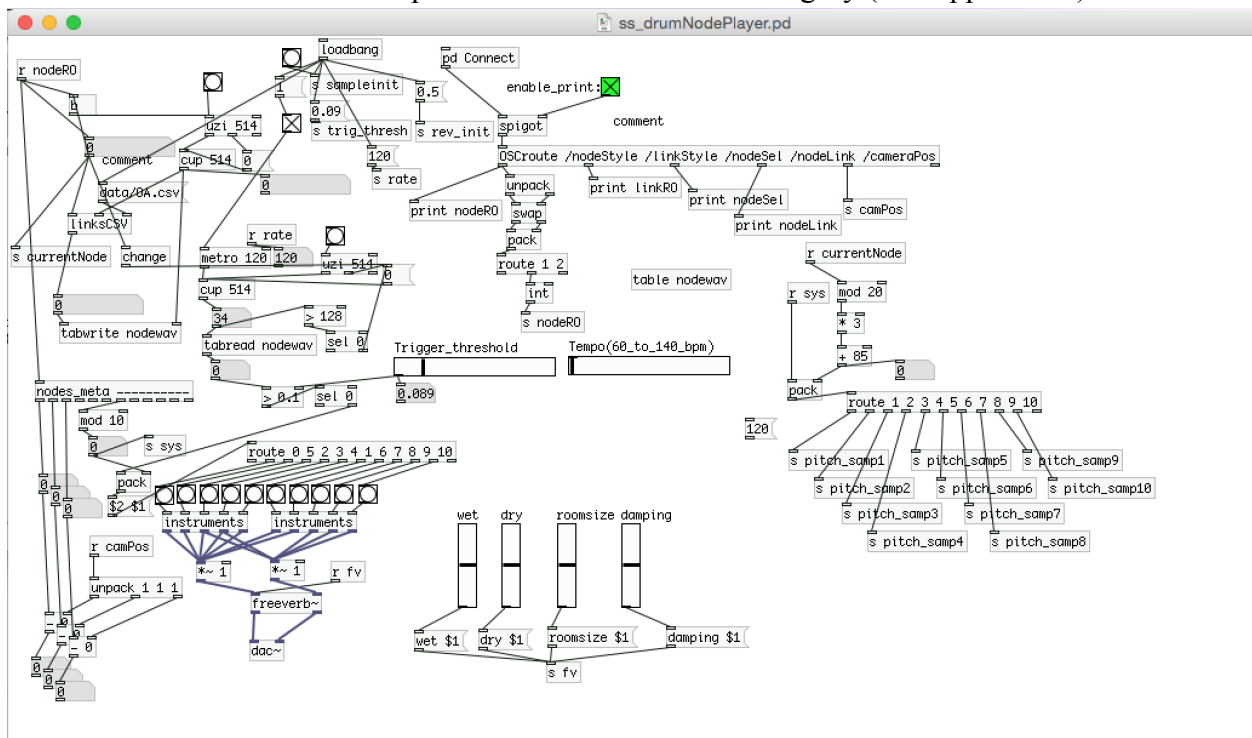
Brand symbol developed for the project



Pure Data Patches used for sound creation

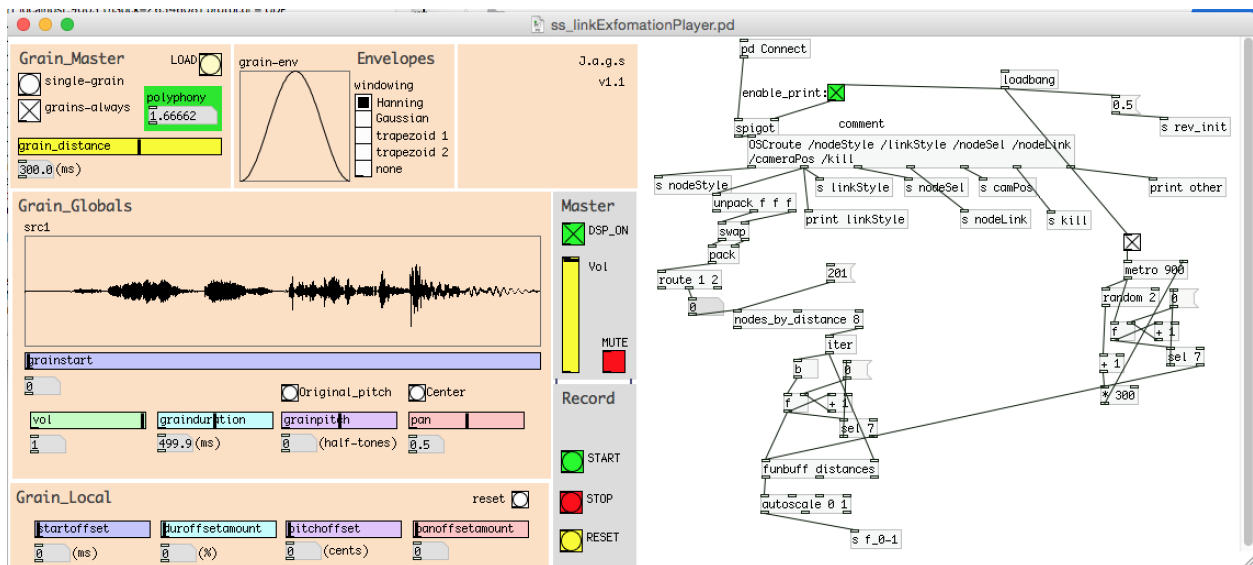
The mechanism developed for realizing the StethoVis unity based tool and the accompanying Pure Data computer synthesis routines were based on communication between the two programs via the Open Sound Control protocol. An Event Bus architecture was developed, which is detailed in Appendix 1. The user could choose from a dynamic list of sonifications as one of the interface chooses of the User Interface. The nomenclature chosen for the Unity program to identify each of the specific sonification techniques was `ss_PatchName.pd`, where PatchName is the specific text identifier for each sonification routine. Here is a list a brief explanation of the routines that were provided and tested by the neuroscience team. Additionally, the type of sonification as described in the Appendix 6 document, DATA Stethoscope Project - Technical Note No 2 are identified with each distinct sonification technique. Please note that the sound synthesis identified below are the exemplars of many dozens of other routines developed for this project. These were the routines that generated the most interest among the user base as the tools were made available

- `ss_drumNodePlayer.pd`
 - Sound used is different for each brain subsystem. Each system in the brain map was assigned a specific “drum” sound. Visual System = Bass Drum, Default System = Tomtom, Auditory System = closed hi hat etc. On node rollover, plays a distinct rhythm for each node.
 - An example of the “data as music” category (see Appendix 2)

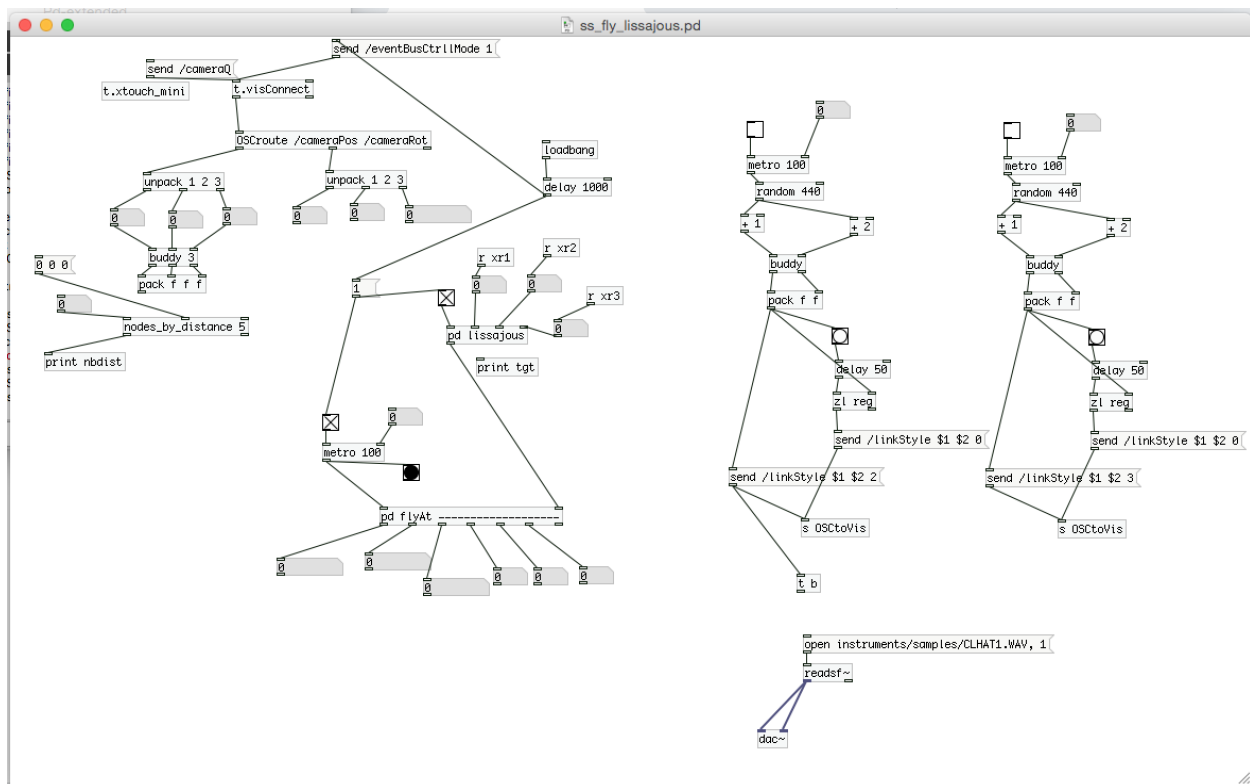


- `ss_linkExfomationPlayer.pd`

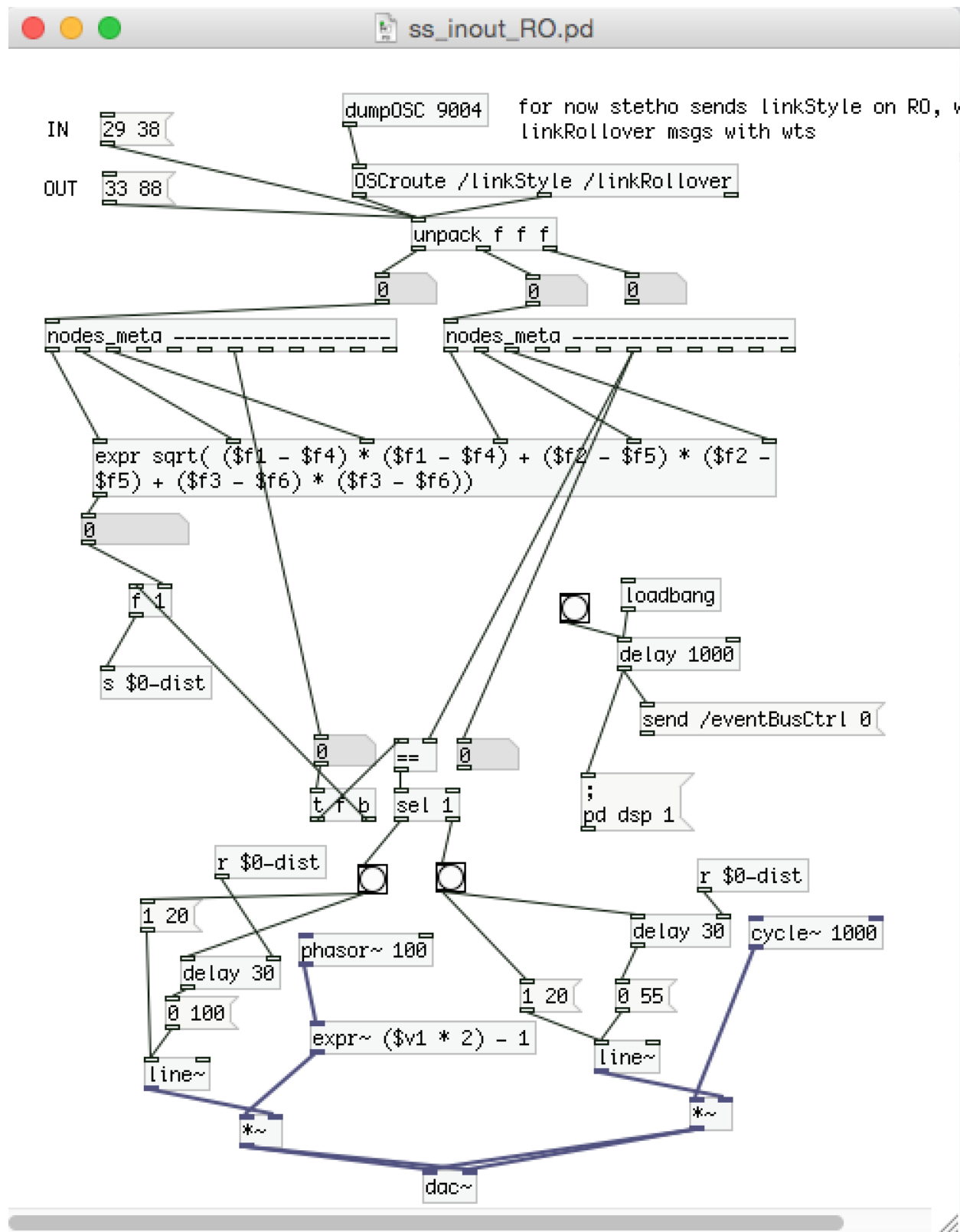
- A granular synth filled familiar musical material is modified by various parameters of the complex network data that consists of the link strengths near the cursor
- An example of “data as anomaly” (see Appendix 2)
-



- ss_ecoSysPolysample.pd
 - See note inside the patch
 - An example of “data as location” (see Appendix 2)

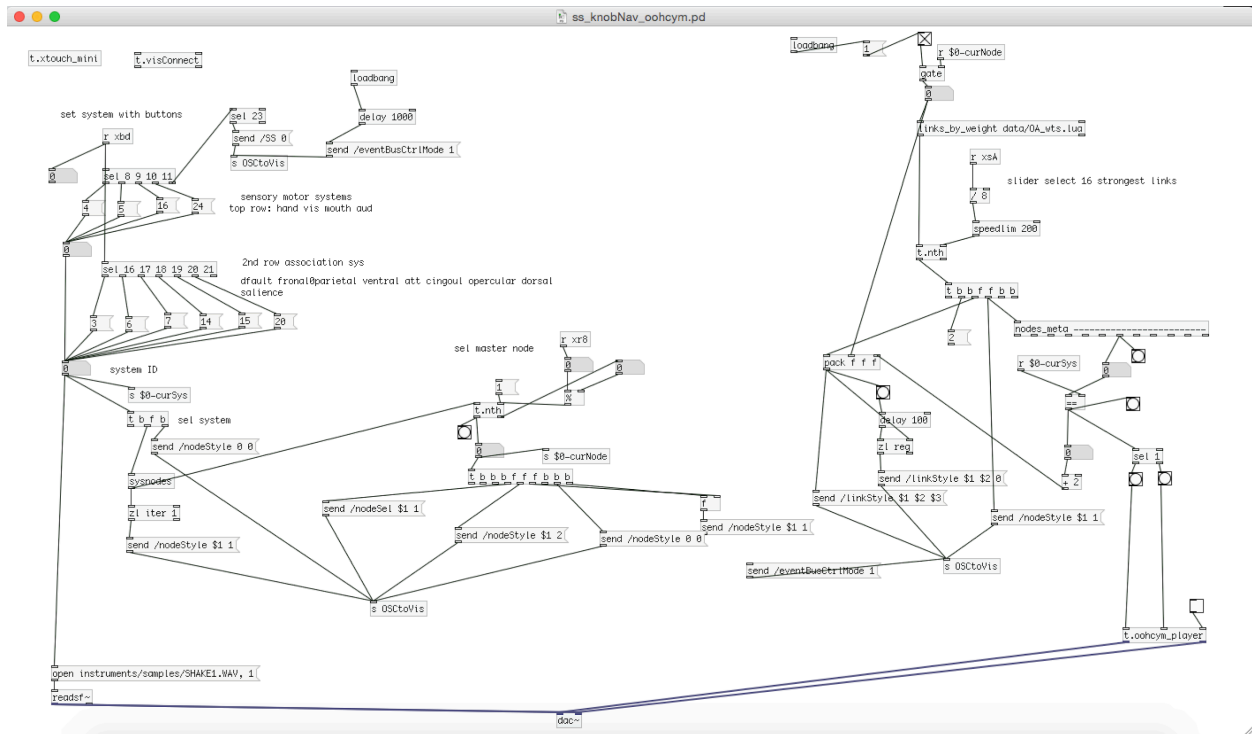


- **Ss_inout_oohcyn_nabors.pd**
 - This patch plays a cymbal sound on links inside the system and a vocalized “ooo” sound of links that represent connections between two systems
 - An example of “Data as melody/harmonic movement” (see Appendix 2)



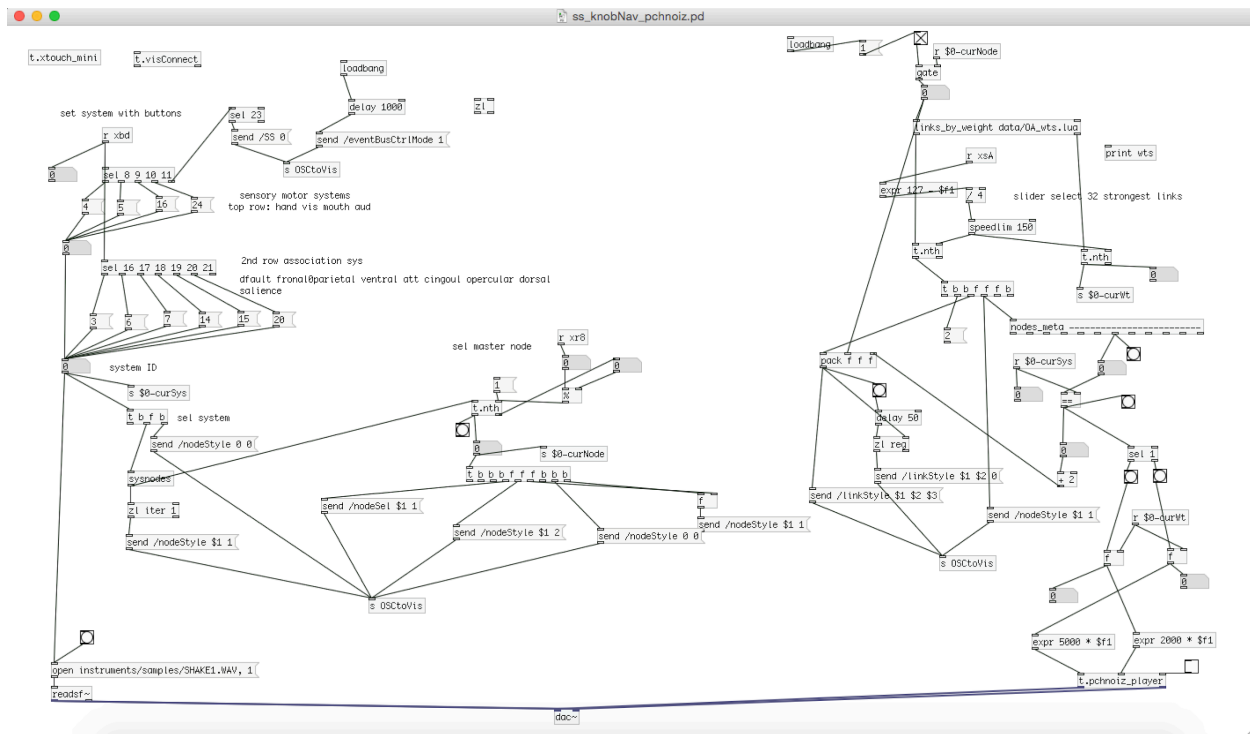
- ss_knobNav_oohcym.pd

- using a Behringer usb midi controller, select system with buttons, a node with knob #8, then slider to show/hear links to most strongly connected 32 nodes. sounds are vocal “ooh” for in-system, cymbal sound for out of system.
- Data as gesture and Data as environment - See Appendix 2

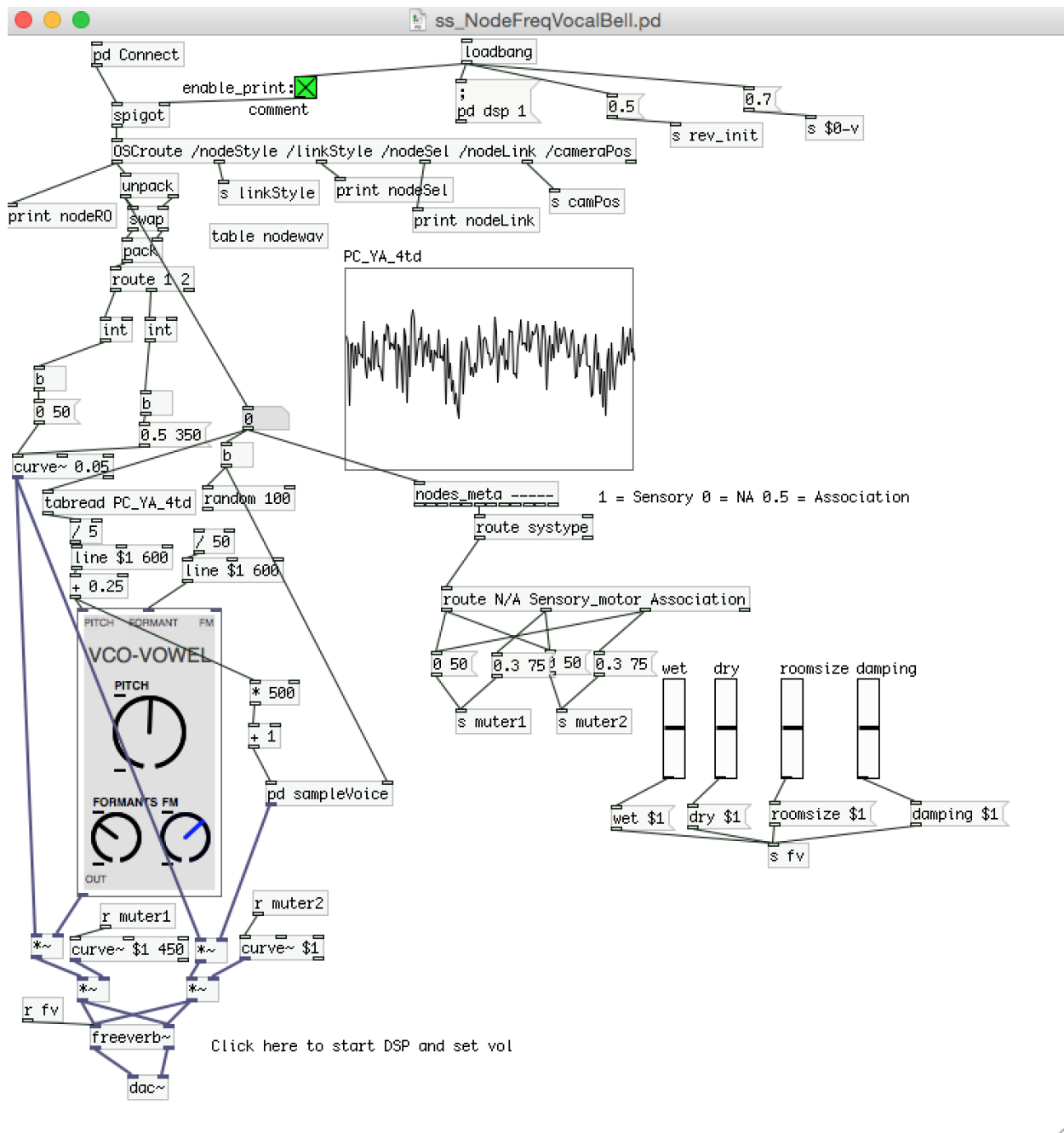


- ss_knobNav_pchnoiz.pd

- using a Behringer usb midi controller, select system with buttons, a node with knob #8, then slider to show/hear links to most strongly connected 32 nodes. sounds are “beep” for in-system, pitched noise for out of system. Pitch of sounds are proportional to strength of internode link.
- Data as gesture and Data as environment - See Appendix 2



- **ss_NodeFreqVocalBell.pd**
 - on node rollover, play a sound for major brain subsystems: a vocal sound for sensory-motor systems, and a bell sound for association systems. Pitch is proportional to ratio of strong intra-system vs. inter-system nodal links.



- ss_directAudificationSineAndTap.pd
 - On node rollover, play sound table sequence based on list of connections to the node.
 - An example of “Data as melody/harmonic movement” (see Appendix 2)

Summary of challenges encountered

- a. We confirmed the difficulty of transdisciplinary collaborations where team members are not co located and heterogeneous (age, gender, profession) as has been documented in the Science of Team Science literature but in this case extended to a wide gulf between scientists and artists practices and professions. A recommendation from this project is to develop specific training methods for transdisciplinary collaboration.
- b. Gaming engine tools in general (Unity in this case) are not sophisticated enough to enable sonification methods to be integrated into the gaming engine. We therefore developed a Open Sound Control event bus interfaced to the Pure Data , a computer music synthesis software systems.
(OSC_UNITY2PD_Event_bus_spec_150831.rtf) Our recommendation is to continue using gaming engines at this point with and interface to state of the art computer music software until gaming engine sonic functionalities are improved.
- c. We have made available to DARPA all the versions of the StethoVis Unity gaming engine renditions up to the performance version StethoVis 1.0.14. Also, the Pure Data codes outlined above as both headed and headless codes are in the repository. This has been a continued resource as we move forward with our next iterations of this research.

(7) Bibliography

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4. Nees, M.A., & Walker, B.N. (in press). Auditory interfaces and sonification. In Stephanidis, C. (Ed.), *The Universal Access Handbook*. New York: CRC Press, pp. 509.
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(7) Appendixes

Appendix 1

OSC_UNITY2PD_Event_bus_spec_150831

DOCUMENT 7 Event Bus Spec – Data Stethoscope Project

Version 1.4

Date Aug 31 2016

Lead author – ed. Tim Perkis, with Scot Gresham-Lancaster, Andrew Blanton + Roger Malina

Vis Listen / Snd Send Port: 9003

Vis Send / Snd Listen Port: 9004

Vis address root: message root is ‘/’ Send ‘/’ + message name, then args. e.g.: /nodeStyle 422 3 [this is a change from previous spec which skipped the leading ‘/’ character. But some OSC parsers, such as the one in Pd, require the leading slash, even though it shouldn’t!]

1. Overview

The **event bus** forms the backbone of the **Stetho** visualization/sonification project, providing a means for coordination and communication between the sound and visual subsystems of the app. The application was split into two separate modules that run as separate processes, so that the best available software development environments can be used for the visual and auditory domains: The game/simulation engine **Unity** was chosen for the visual side, and the open source synthesis design language **pd** was chosen for the sound development side. While each of these multimedia programming systems provides both visual and sound development affordances, each is weak in the subdomains outside its specialty.

We’ve chosen **Open Sound Control** (OSC) as the transport layer format for inter-process communication between the visual and sound processes. OSC is an IP-based communications protocol developed for communication in musical and multimedia systems, and has been widely adopted in the musical instrument industry and beyond, becoming a popular standard for control and communication in real-time systems.

2. OSC background information.

What follows is not a description of the actual internal structure of osc packets and messages, but a description of the strings needed to specify osc messages to all basic OSC sender/receiver drivers, available for Unity and all major computer languages. For more detailed information on the osc protocol, see the intro page at opensoundcontrol.org.

We are using a subset of OSC capabilities that don't demand a deeper dive into the actual physical formats. At root OSC messages are sent as UDP packets on any IP-based network, and part of the driver configuration for a OSC sender is setting an IP address and port that all messages will be sent to. (This is different than the OSC **address**, specified below.)

OSC messages can be thought of having two main parts, the **address** and the **payload**. The address appears first in the message; it does not represent an actual IP address but rather is a convenience, marking either the intended handler(receiver) or the source of the message. By convention the address is a string without spaces, which may have separate sections delimited by '/' characters, similar to a unix path.

What I'm calling the payload is the rest of the message, the following message data, which may be any mix of values of type string, integer or float. Examples of legitimate OSC messages:

```
foo/bar/333 tim 33.0 scot 99 veena 44.0  
camera 34.0 55.454545 345.44 666.45454 8.0 12.9
```

For a more specific example, a synthesizer which has synthesis parameters settable by OSC messages might respond to messages like:

```
voice/1/env/attack 44
```

which may specify that upon receiving this message, the attack envelope on voice number 1 should be set to the value 44. Conversely, a controller interface – say a controller box, which sends out messages corresponding to sliders and knobs, would use the address to specify the **source** of the message, not its intended recipient:

```
slider/12 127
```

reports that slider number 12 has been set to the value 127.

Stetho message format – general principles.

This document will define the specific set of messages that will be sent in both directions between the visual and sonic subsystems, chosen with the intention to:

1. allow the sonic system to simulate any possible user action in controlling current visualization state, such as the appearance and point of view and
2. keep the sonification system notified of the current state of the visualization system, and any user interactions as they happen.

This document is of necessity a work in progress. The heart of this document is the Stetho event dictionary section below, defining the format of the messages we will be sending on the bus. This list will undoubtedly change as we develop the specification of the user interface, and fix on the capabilities of the system.

The basic principle is that anything doable by a user manipulating the visual systems user interface should also be performable by event-bus messages sent to the visualization system on this bus, and that all relevant changes to the visual app's state, either through user action or otherwise, should be reported to the sound system so that relevant matching sonic events can be generated.

3. Stetho event dictionary.

messages sent either visual → sound or sound → visual

Sonif type process change flow:

- 1) selection cleared and clearSel message sent
- 2) eventBusCtrlMode set to 0 (off)
- 3) Kill message sent over event bus
- 4) wait 0.5 secs
- 5) use cmd/terminal to start new pd process

Sonif type processes are ended via event bus Kill message (new started after 0.5s as described above)

Message	Sent on	Description	comment	Priority
cameraRot x y z	camera rotation		Euler angles (vis->snd only)	finished
cameraPos x y z	camera position changed	x y z point location of camera in space, relative to the data set		finished
cameraLookAt x y z		x y z point location of camera in space, relative to the data set	(snd->vis only)	finished

dataView n	select current target from multiple brain views		global state: sets target view of subsequent sound->vis EventBus messages.	5
cameraFOV angle	camera zoom change			5
cameraQ	request current cam orientation and position	response should be cameraPos x y z and cameraRot x y z msgs	snd->vis only	
clearSel()	clear all selection	called on EventBusMode change and just before sonif mode change		
nodeStyle(nodeID style)	node rendering style	if nodeID == 0, set all nodes to style Not necessarily always sent on UI stimulus, but when the screen changes the message should ALWAYS happen	style codes: 0=off, 1=minimized, 2=normal, 3= highlighted	finished (but should not send on initial data creation)

nodeSel(id, turnOn, showEdges)	intentional selection of node	report node selection by mouse click when eventBusCtrlMode = 1, doesn't change style when eventBusCtrlMode = 0, style is changed	node number id = node id turnOn= 0/1 showEdges = 0/1	finished
linkStyle (n1 n2 style)	link rendering style	node1 node2 style. if n1=0 and n2 = 0, apply style to all links. Not necessarily always sent on UI stimulus, but when the screen changes the message should ALWAYS happen	style codes: 0 = off, 1 = dim or flickering 2 = normal 3 = highlighted	finished
linkSel(id1, id2, select)	intentional selection of link	report link selection by mouse click when eventBusCtrlMode = 1, doesn't change style when eventBusCtrlMode = 0, style is changed	node1, node2, weight id1 = node 1 id id2 = node 2 id select = 0/1	finished
sysSel (sysID)	sys selected		send with 0 value when current brain system is unselected	2
sonifTypeSel sonifID	user selects sonification type		sonifID = a name string? when sonifID is null (or 0?), turn sonif off?	3

sonifOn (0/1)	user turns sonification on/off			4
eventBusCtrlMode (0/1)	sonif turns on/off styling capabilities of UI cursor (but not selection, which is always on)		0 = off 1 = on	finished
Kill ()		when received by a sound process, it should perform an orderly exit, closing its port on the bus and quitting.		
text (str)	pd->visual	Display provided string argument in text display area at top(or bottom?) of screen.	Clear text area if received with no argument or empty string argument. Each msg received replaces current text displayed, NOT adding text to display.	
thresMin(float)	Min threshold changed			
threshMax(float)	Max threshold changed		Only relevant in density mode	

threshMode(0/1)	Change threshold mode (value <-> density)			
-----------------	--	--	--	--

4. Invoking Pd processes from the StethoVis process.

Sonification processes, as implemented by pd patches, are transient: they are started by the visualization process by some form of ‘system’ command line invocation of Pd, passing in the name of the desired sonification patch as an argument to the Pd call. They should terminate when sent a /kill message on the event bus by the visualization process.

Pd-extended needs to be installed in the default location: for windows, in C:\Program Files; for os x, in /Applications.

The visual app needs to maintain a variable setting the base path location of the stethovis pd files, and use it in constructing the command line invocation of a patch. The pd code base, as kept on github in [datastethoscope/pd](#), should be cloned from github. At the top level of this installation, all the main sonification files will appear, following the naming convention

ss_<nameOfSonificationStrategy>.pd

I recommend populating a select widget in the visual app UI which is populated by listing all of these files, clipping off the ss_ prefix and .pd suffix.

The sonification strategy on selection can be invoked by a system call with this command line:

OSX:

```
/Applications/Pd-extended.app/Contents/Resources/bin/pdextended -nogui  
<path_to_our_pd_directory>/ss_someSonificationStrategy.pd
```

on windows: (untested by me.)

```
C:\Program Files\pd\bin\pd.com -nogui <path_to_our_pd_dir>/ss_someSonification.pd
```

see these pages for more info on cmd-line invocation:

<https://puredata.info/docs/faq/commandline>

<https://puredata.info/docs/faq/how-do-i-run-pd-from-the-command-line>

UTD ATEC ARTSCI LAB Grey Paper

#4.1

DATA LISTENING: Techniques and Classifications

FEB. 15, 2019, roger updated feb 27

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Abstract:

This white paper is the result of years of research into developing Techniques and Classifications that are unique to our research into converting data into audio. We refer to this as 'DATA LISTENING' (Listening to Data) while others often use the term 'Data sonification'. We have identified three distinct techniques and three distinct Classifications for achieving this result. This can be then converted to a 3x3 matrix that gives 9 distinct approaches to Learning, Exploring and Testing our LISTENING TO DATA approach

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1. Introduction
2. Techniques
 - 2.1 pattern creation
 - 2.2 Monitoring
 - 2.3 search and discovery
3. Classifications
 - 3.1 Analog Conversion
 - 3.2 Synthesis
 - 3.3 Signal Processing of Sonification
 - 3.4 3x3 matrix of 9 techniques/classification types
4. Conclusion
5. Appendix: Further explanation of each of the technique/classification matrix

6. Acknowledgements

1. Introduction:

This white paper is the result of 7 years of research into developing Techniques and Classifications that are unique to the UTD ATEC ArtSciLabn research into converting data into audio. We refer to this as 'DATA LISTENING' (Listening to Data) here, with the same definition as the term 'Data sonification' we also use. We have identified three distinct techniques and three distinct Classifications for achieving successful conversion of data to sound that can be understood. This can be then converted to a 3x3 matrix that gives 9 distinct approaches to Learning, Exploring and Testing our DATA LISTENING (Listening to Data, Data Sonification) approaches.

2. Techniques of Data Listening:

In order to realize the workflow that we are suggesting there is a need to identify a slightly different set of techniques and classifications of sonification. There are many ways to take raw data and convert them to sounds of an almost infinite variety. Categorizing each of the techniques that can be realized with the distinct classification of audio types that can be created using computer music software techniques is essential.

To most effectively do this we have identified three general techniques of interacting with computer generated audio. What we mean by a technique is ?

2.1 First is the technique of **pattern creation**. Data is often held in computers in arrays. The rows and columns of a spreadsheet are familiar, where rows of information are organized by distinct columns of repeated information. Name, Sex, Age, Weight, Height for example. These columns can be sorted, filtered, etc. leaving a set of distinct numbers on each row. In the case of the example each array associated with a row would be have four members, something like Bob, male, 37, 190, 5'10". In this case, Bob is not a value, but everything else can be construed as a value. This can be thought of as a 5 member pattern. These discrete number arrays lend themselves to being used scaled and stepped through with all the various computer music software packages. They are all designed to deal with arrays of repeated numbers as parameterized fields of pitch, amplitude, filter etc. (see appendix 2 for a list of parameterizable physical quantities)

2.2 The second technique, **monitoring** (soundscape) is more architectural in nature and relies on the "sonifier" to create a soundscape from the data. Each element in the sonification has an identity and the listener is tasked with listening to the resulting environment as an "Acoustic Ecology". This concept may be unfamiliar to some, but it is a big part of the way that we use audio to interact with the world. We are presented with many layers of sound in all sorts of acoustic environments. We are experts at ascertaining the details of each new environment and isolating the identity of the individual sound and placing them in the mental map of the the situation we are listening into This technique is an approach to this very real if seemingly

abstract approach to listening to data. All modern computer musics have systems for this sort of mixing of elements into acoustamatic soundfields. All modern mixes can be thought of as being created in this context.

2.3 The third technique, **search and discovery**, is an extension of the second. Once the audio environment is created, it can be explored. The user/listener can use the techniques of navigation to move throughout the “acoustic ecology” and discover relationships and differences in this virtual space. This moves the act of sonification into the realm of gaming, in that it assumes that the acoustic space created will have discoverable artifacts that are the complex combination of navigation and orientation in a new audio “data world”. The music technology techniques for this sort of computer music realization are just becoming a part of the sound designers tool kit and are closely associated with the sound production for gaming, virtual and augmented reality etc. These are the newest techniques of audio production, but at the time of this writing they are finally fully a part of the audio industries production capabilities.

These three general techniques can be realized with three separate classifications of computer sound synthesis. Analog conversion, Synthesis and Signal Processing

3. 0 Classifications of Data Listening

Definition of classification: what we mean by a classification is ?

3.1 Analog conversion is the direct conversion of data into sounds. The metaphor of the record needle may help in understanding the fundamental principle of this approach. The data, in this case, can be thought of as the raw contour of the data. By dragging the phonograph needle over these contours one gets the direct sounding of that groove. The speed and pressure of the needle itself give varying results, but the analogy (or analog) of the data is sonically represented. This is the mainstay of computer music production. The audio buffers, signal generators and sound synthesis routines are designed to take sets of parameters at both audio and control rates to play both discrete and continuous notes and sounds. Each sound event can also be embedded with discrete cognitive attributes (frequency and amplitude modulation, filtering, phase shifting etc.) that are fully integrated into modern computer music languages

3.2 Synthesis requires remapping of the data. In this case the numbers can represent direct mappings of audio qualities. One number list can be interpreted as pitch, another amplitude, another as amount of reverb etc. etc. While the most prevalent style of data sonification, this abstract remapping of quantities presents a current key problem with the conveying sonifications. How does the user understand that the pitch represents some notion of a data column? Why is pitch the height of the user and not the age, for example? This problem is what has prompted us to not only include speech markers to help label and communicate to the user/listener, but also to proceed the user experience with a training module that orients the user/listener to the data remapping first as an abstract concept and later with the details of the remapping in the actual instance of the specific use case.

The final classification, **signal processing**, is a further level of abstraction in sonification creation. One assumes that material familiar to the user/listener (a song, podcast etc.) is being sent through a digital signal processing box. The parameters of data are applied to the the settings of various signal processes. This could be filters, reverb, panning of the sound to various speakers, amplitude and/or frequency modulation, etc etc.

Given all these options a wide array of potential combinations is made available for testing and realization. If a matrix of the 3 techniques and 3 classifications are made, a large and distinct catalog of the 9 resulting general sonification types emerge:

1. 3 x 3 Table of Sonification Techniques and Classifications

Techniques x Classifications	Pattern Creation	Monitoring (Soundscape)	Search and Discovery
Analog Conversion (Audification)	Data as gestalt - the discrete representation of the data. Individual data “packets” or icons of sound shaped by the scaled data - raw sound buffers, waves from time series data	Data as environment - Mixing the abstract electroacoustic space with a mixing board, combining and mixing levels with a midi controller	Data as presence - the combination of sound possibilities driven by interaction and navigation - Data Forest
Digital Synthesis (Sequencing)	Data as melody or harmonic movement - Musification of data stethox menu item 1, 2, 5 for example Use case 4C - 4A <i>Most common technique (bar chart: as melody or chord)</i>	Data as gesture - a sea of sequences that are experienced as a sound field, loops or data driven processes mapped on a 2d surface, Texas gong, example Use case: 1	Data as music construction - Fragments of data set are combined horizontally and vertically (eg Tunification or Musification)
Signal Processing (Exformation)	Data as extrinsic: parameter change - freq., pitch, tone, (stethox menu 3 & 4) Use Case: 4B	Data as location: familiar or biological signals and audio material displaced by location and reverb (sound mapping (real world and virtual))	Data as anomaly: enigmatic sonic configurations that make the familiar, unfamiliar. Playing music or familiar speech (podcast) through various parameterized digital signal processing

			(resonate filter, delay, reverb etc.)
--	--	--	---------------------------------------

These 9 types can be driven by both automatic and real time reactions. Some of these mechanisms like the melody and harmony instances , constitute the majority of the work done and inherit all of the legacy of music. These are then a special case that need to be handled via the understanding of Music cognition theory.

While there is an implication of time in the description of these sonification types, it is the fixed experience of time that starkly differentiates audio from visual representation. Visual information can be non-linearly scanned and features can be extracted from large sets of information in a very short time. A sonic representation of the same information would require bundles of scaled time auditions or highly verticalized sound bursts that nonetheless would take a succession of auditions to differentiate. However the detail and accuracy of this dimensional representation is much more available in this auditory representation. To that end, the visual provides a cursory but almost instantaneous overview of large data fields, while sound has the unrealized promise of a depth of information comprehension and tactile interaction that the visual simply can't provide.

4. Conclusion

This is an introduction to a very complex and ongoing set of research trajectories we have been examining over the last decade. This has required the construction of new tools and tests of those tools with individuals, to more clearly understand the usefulness and focused use cases for each of these very different approaches to Data Listening :

To provide a little more detail on each of the Techniques and Classification types we have identified, please refer to the Appendix below for an outlined overview.

Appendix:

Here is a an outline that goes further to explain each of the cells of the Techniques x Classifications matrix

1. Audification

a. Pattern Creation (record needle)

- i. Data as gestalt - the direct sounding of the data. Individual data “packets” or icons of sound shaped by the scaled data
 1. Data Handling: Data stream created as time series data flow (time and amplitude scaling)
 2. Csound design idea:Csound design idea:
 - a. ORC =

- i. sample playback
 - ii. graphic eq
 - iii. pvoc for scaling
 - b. SCORE = looped data streams fragments
 - ii. [No Use Case at this time](#)
 - iii. Descriptive Paragraph: This technique makes it possible to hear the raw information as a sound buffer. Each dimension of the data set can be thought of as a “groove in a record”. The user can manually scrape across the data or play it as a waveform.
 - b. **Monitoring Soundscape (mixer - listening posts)**
 - i. Data as environment - electroacoustic space
 - 1. Data Handling: Information segmented into many separate loopable information packets
 - 2. Csound design idea: repeating stk physical model synthesis played by repeated data streams
 - ii. [No use case at this time](#)
 - iii. Descriptive Paragraph: This technique makes it possible to hear the raw information as a sound buffer. All the parameters of the data set are playing in asynchronous loops. The user has a model of a mixer for each data stream and mixes and compares the audio files.
 - c. **Search and Discovery (3d trip through data)**
 - i. Data as presence - the factory - the forest - the combination of sound possibilities driven by interaction and navigation
 - 1. Data Handling: Information segmented into many separate loopable information packets
 - 2. Csound design idea: repeating stk physical model synthesis or pitched sound samples played by repeated data streams in 3d locations with the addition of xyz camera position that gives HRTF binaural response to the soundscape.
 - ii. [Use Case: Data Forest with Bio and Audio sensor data from actual forest](#)
 - iii. Descriptive Paragraph: This technique makes it possible to hear the raw information as a sound buffer. The data has the attribute of a physical distribution in 3d space of discrete data “packages”. These 3d models can be either real models (brain model, landscape etc.) or virtual models (complex network, model of protein molecule, etc.) The sound buffers are distributed around 3d space. A panning, amplitude and reverb stereo mix is used to model distance from a sound source. This can be extend to binaural. This would be a navigable 2d grid that uses gaming style loop playback and the user can just drop the sounds where they want on the map. The user navigates in that model in one of two ways:
 - 1. Exploring the map by traveling through the virtual three space defined by this audio spatialization mapping (discovering the interesting or informative paths)
 - 2. Taking those discovered paths and supplying a "roller coaster ride" or fixed path through the map to inform others of discoveries previous users of mode 1 have found. Educational and/or informative to follow up users
- These 2 modalities use the same audio engine and module and only differ in the modules that run the "ear camera" ;-) view. One is free on the map, the other is set on a predetermined path.

2. Sequential

a. Pattern Source Creation (cognitive perceptual looping of musical material)

- i. Data as melody or harmonic movement
 - 1. Data Handling: Information segmented into many separate loopable information packets. Scaled and remapped to diatonic
 - 2. Csound design idea:
 - a. ORC = stk physical model synthesis
 - b. SCORE = looped data streams fragments as hockets
- ii. Use Case: Circos last menu item (labeled Melody)
- iii. Descriptive Paragraph: This technique is quite probably the most ubiquitous sonification technique. This is the vector for the most distinct types of the application of “musification” ideas. A simple and ubiquitous example would be where a standard visual bar chart is converted to a melody. Each of notes of that melody have the option of sounding in a varied and multidimensional way. Additionally, the time between the beginning of each note event can reflect some aspect of the data set. (waveform, filter, amplitude, attack time, decay time, etc.) The use of steady playback reflects a standard and regular data sample rate. A non regular playback instance reflects the temporal relationship of each data point to the next.
- iv. Here is a breakdown of classic music approaches (mesostructures in Carl Road’s parlance)
 - 1. Repetitions the most basic musical structure: iterations of a single sound or group of sounds. If the iteration is regular, it forms a pulse or loop.
 - 2. Melodies sequential strings of varying sound objects forming melodies, not just of pitch, but also of timbre, amplitude, duration, or spatial position.
 - 3. Variations iterations of figure groups under various transformations, so that subsequent iterations vary.
 - 4. Polyphonies parallel sequences, where the interplay between the sequences is either closely correlated (as in harmony), loosely correlated (as in counterpoint), or independent; the sequences can articulate pitch, timbre, amplitude, duration, or spatial position.

b. Monitoring Soundscape (cognitive perceptual looping of sound rendering)

- i. Data as gesture - a sea of sequences that are experienced as a sound field
 - 1. Data Handling: Information segmented into many separate loopable information packets
 - 2. Csound design idea: repeating as additive synthesis or stk physical model synthesis played by repeated data streams
- ii. [Use Case - Texas Gong to Tree of Life Gong](#)
- iii. Descriptive Paragraph: This technique is has no sequential aspect. The entire data set is distributed in a 2 dimensional grid. The user “strikes” the grid in different places and the information beneath that specific point in the 2d map plays a unique sound based on the the multidimensional parameters of the data set under investigation. The Texas gong is an example of this as is the drum interface that was used in the Connectome project. The user touches a specific point to excite the sound. It is even better if the velocity of the excitation is integrated, the user then “strikes”

the data to hear the data at various depths and exciting various levels of interaction between parameter fields.

c. Search and Discovery (cognitive perceptual looping of sound + music rendering)

- i. Data as music - most common realization (bar chart as quantized melody)
 - 1. Data Handling: Information segmented into streams of scaled and remapped Melody lines for each major parameter. Less important parameters mapped to filter, amplitude and rhythm quantization
 - 2. Csound design idea: repeating as additive synthesis or stk physical model synthesis played by repeated data streams
- ii. [Use Case - Chess Board sonification used as part of the 9e2 performance in Seattle in](#)
- iii. Descriptive Paragraph: This technique makes it possible to hear the raw information as a music playback environment. The data has the attribute of a physical distribution in 3d space of discrete harmonic “packages”. These 3d models can be either real models (brain model, landscape etc.) or virtual models (complex network, model of protein molecule, etc.) The playback Buffers are distributed around 3d space. A panning, amplitude and reverb stereo mix is used to model distance from a sound source. This can be extend to binaural. This would be a navigable 2d grid that uses gaming style loop playback and the use can just drop the sounds where they want on the map. The user navigates in that model in one of two ways:
 - 1. Exploring the map by traveling through the virtual three space defined by this binaural mapping (discovering the interesting or informative paths)
 - 2. Taking those discovered paths and supplying a "roller coaster ride" or fixed path through the map to inform others of discoveries previous users of mode 1 have found. Educational and/or informative to follow up usersThese 2 modalities use the same audio engine and module and only differ in the modules that run the "ear camera" ;-) view. One is free on the map, the other is set on a predetermined path.

3. Extrinsic (Exformation)

a. Pattern Source Creation (cognitively informed data scrub for patterns)

- i. Data as extrinsic parameter change - freq., pitch, tone
 - 1. Data Handling: Information segmented into streams of time and amplitude scaled KR levels for each major parameter. Less important parameters mapped to less perceptually dominant audio effects
 - 2. Csound design idea: User chosen mp3 files played through a chain of dsp. Graphic eq, panning, reverb, delay etc
- ii. [Use Case - not at this time](#)
- iii. Descriptive Paragraph: This technique requires the user to select or upload a sound file they wish to listen to, hopefully something they are familiar with (favorite artist, podcast that they listen to, etc.) This audio stream is fed into a multi parameter digital signal procession “black box”. The black box can dynamically modify the audio as it plays back. Each parameter of the time series data set is changing the various settings on

the black box. The box itself has the acoustic parameters mapped by cognitive priority. The box itself has the acoustic parameters mapped by cognitive priority. Possible PsychoAcoustic ranking:

1. Panned Left = 0 - Right = 1
2. Highs filtered
3. Lows filtered
4. Reverb
5. Mid Range filtered
6. pitch shifting

b. Monitoring Soundscape (Wandering the Radio Dial of an extra dimensional radio playback)

- i. Data as location- familiar material displaced by location and reverb
 1. Data Handling: Information segmented into streams of scaled and remapped, Three dimensional placement derived from three major parameters
 2. Csound design idea: User chosen mp3 files played through a chain of binaural and reverb modules
- ii. [Use Case - Nothing at this time](#)
- iii. Descriptive Paragraph: This technique requires the user to select or upload a set of many sound file they wish to listen to, They systematically assign those sounds to a grid. The sound files are distributed around 3d space. The playback of the sound file is psychoacoustically perturbed by the part of the data set represented by that sound in a looped cycle. (see 3c for detail on psychoacoustic parameter mapping on a per group basis) A panning, amplitude and reverb stereo mix is used to model distance from a sound source. This can be extend to binaural. This would be a navigable 2d grid that uses gaming style loop playback and the use can just drop the sounds where they want on the map. The user navigates in that model in one of two ways:
 1. Exploring the map by traveling through the virtual three space defined by this binaural mapping (discovering the interesting or informative paths)
 2. Taking those discovered paths and supplying a "roller coaster ride" or fixed path through the map to inform others of discoveries previous users of mode 1 have found. Educational and/or informative to follow up users

These 2 modalities use the same audio engine and module and only differ in the modules that run the "ear camera" ;-) view. One is free on the map, the other is set on a predetermined path.

c. Search and Discovery (play your own music through data perturbed effects)

- i. Data as anomaly - enigmatic sonic configurations that make the familiar, unfamiliar
 1. Information segmented into streams for each column, scaled rhythmically and amplitude
 2. Csound design: spectral restructuring via pvoc on both the time and frequency domain.
- ii. [Use Case - Circos \(stethox\) menu item 3 and 4 \(Exformation & écureuil\)](#)

- iii. Descriptive Paragraph: This technique requires the user to select or upload a sound file they wish to listen to, hopefully something they are familiar with (favorite artist, podcast that they listen to, etc.) This audio stream is fed into a multi parameter digital signal procession “black box”. The black box can dynamically modify the audio as it plays back. Each parameter of the time series data set is changing the various settings on the black box. The box itself has the acoustic parameters mapped by cognitive priority. Possible PsychoAcoustic ranking:
 - 1. Panned Left = 0 - Right = 1
 - 2. Highs filtered
 - 3. Lows filtered
 - 4. Reverb
 - 5. Mid Range filtered
 - 6. pitch shifting

Acknowledgements

We thank all the members of the Data Stethoscope team for their participation on the development of these ideas: Gagan Wig, Tim Perkis, Andrew Blanton, Adnan Syed, Judd Bradbury, Michela Chan, Neil Savalia, Cassini Nazir, Kristen Duepree and Make or Break gaming company

Appendix 3: Screenshots of Data Stethoscope Tool

These can be seen and downloaded at:

https://drive.google.com/drive/folders/0BzT0_aIIercfjNXOU5uOXFEdlc4b29oa3A4bGoteXE2dE9kS1oxcDdjaC1XWjVUekJySjQ

Appendix 4: Access to “Data Stethoscope Demonstration Videos”

These can be seen at:

<http://bit.ly/DataStethoscopeVideos>

Appendix 5: Data Stethoscope 9E2 Performance Document <http://bit.ly/9e2performanceDoc>

Abstract:

Data Stethoscope for the Brain Connectome / Oct 28, 2016 for the 9E2 event at the King St. Station in Seattle. A project involving the Data Stethoscope project at UTDallas was asked to “perform” with a multimodal research tool set for examining complex networks derived from fMRI data. 9e2 was an art exhibition and performance series in Seattle commemorating “9 Evenings: Theatre & Engineering”, an iconic exhibition 50 years ago in New York that sparked a new era of collaboration between artists, scientists, and engineers”. This project represents the ongoing research investigating new techniques for not only representing data as visual images, but also accompanying those visual images with sound realizations of the data. This paper describes aspects of the the processes involved in the three unique interpretations of data that were presented in performance at the 9E2 event in Seattle that evening. The performance of the software and data developed for this project is part of a research methodology that involves art, design and humanities methods as part of the scientific method used.

Article:

Introduction:

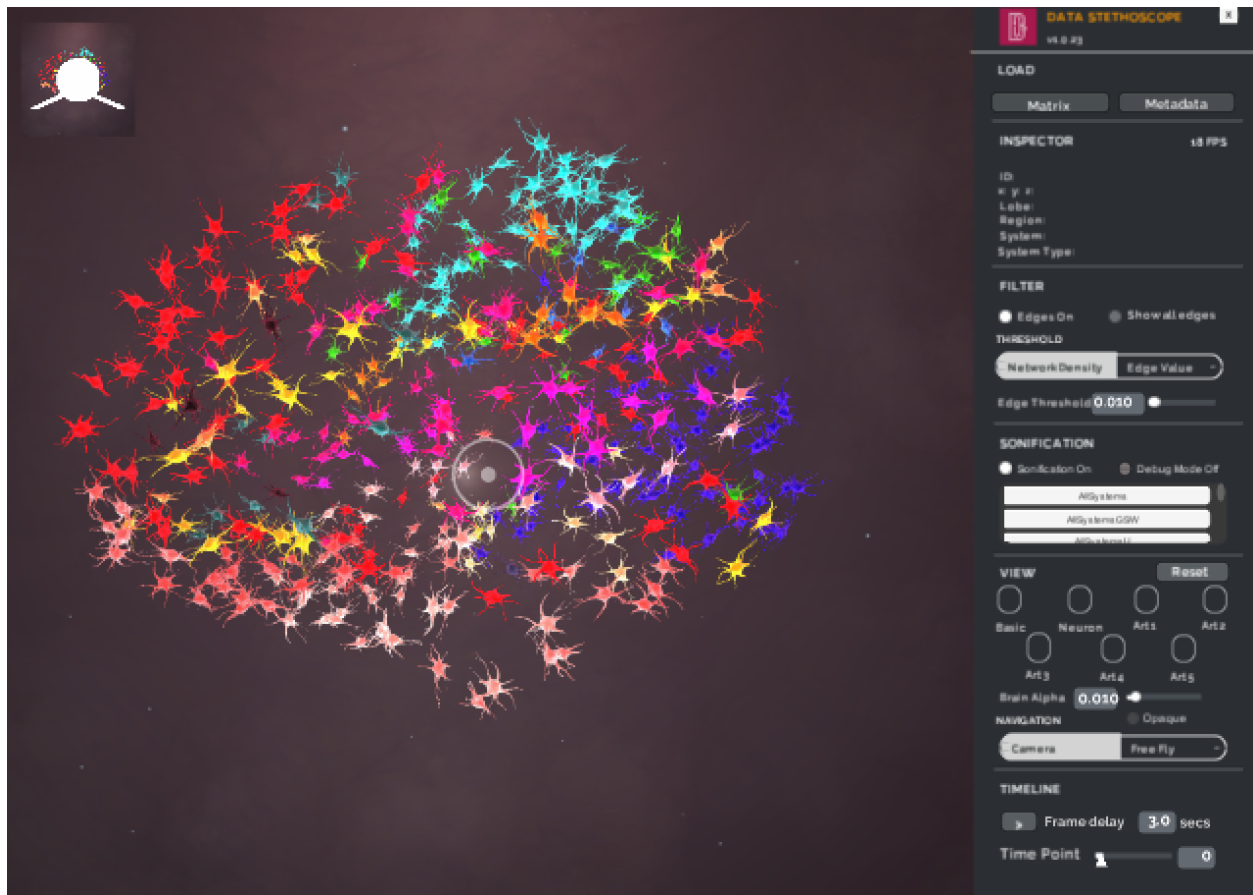
The Data Stethoscope project at UTDallas where the artist participants were asked to “perform” with a multimodal research tool that had been developed as part of a specific set instrument building for examining complex networks derived from fMRI data specifically with the integration of a visual Unity based rendition of the neural networks and sets of audio synthesis algorithms derived from the same information.

In this article we will examine the evolution of a performance from initial planning to actual realization, paying attention to how the final realization varied from the initial conception and the factors that lead to the eventual changes in the nature of the performance itself. There was a challenging problem put forward with the tool that was developed for the research of complex networks derived from fMRI brain scans. The artists involved were asked to use the tool developed for the neuroscience as the performance instrument.

The decision to formulate the collaboration in this context had many interesting side effects that led to unexpected paths of frustration and discovery for all involved. Developing any new approach to what seem to be simple intuitive solutions can often lead to the sort of conflict of expectations that most deep collaborations are fraught with. Science is focused with tight sets of demonstrable steps that are created from known and proven previous work. Art, on the other hand, depends on a much looser criterion of actions within the scope of the craft of the specific artist and the intent to create a user experience that inspires resonance that might not even have the scientific prerequisite of clear understanding, but will elicit a reaction from a witness to the “creative act”. The asymmetry of these two sets of almost unrelated expectations is at the crux of the unique circumstance of Art/Science collaboration.

In this case, there was ongoing work done in the Center for Longevity Studies at UT Dallas at a neuroscience lab establishing a principle of specific changes in the interconnectivity of specific neural systems that was demonstrable with careful analysis of the fMRI data. The interconnections from within specific neurological systems and between differentiated systems demonstrated measurable change from

the scans of individuals of increasing age.(reference Gagan paper) The task of the project was to create a visual and auditory representation of this finding to help support that conclusion. There was the additional further goal of establishing new techniques for using new computer resources in gaming and computer music to create a new class of tool that we were calling a “data stethoscope”



Our initial research had lead us to the conclusion that there was a need to organize a performance to demonstrate the use of the visual and auditory representational tool that we had been refining. To that end we found that there was an opportunity to take part in the 9E2 art exhibition and performance series in Seattle “commemorating “9 Evenings: Theatre & Engineering,” an iconic exhibition 50 years ago in New York that sparked a new era of collaboration between artists, scientists, and engineers.¹ The process of the initial proposal, the following technical redefinition, once the invitation was made and then the final state that the performance was framed, is a telling evolution of the realities of envisioning, planning and performing new media work. This type of work involves envisioning, creating and then performing on instruments and in media environments that have never existed before. The compromises and adjustments that are made as the performance dates approach tell an interesting story of how new media work is self referentially changing in the context of vision and reality.

¹ 9 evenings : theatre and engineering. — Edited by Pontus Hultén and Frank Königsberg. — [New York] : Experiments in Art and Technology : The Foundation for Contemporary Performance Arts, [1966]

The initial proposal

Here is the text of the original proposal that lead to the invitation to participate:

This performance is based around a “data stethoscope” approach to investigating the use of sonification, or the conversion of data into sound, to “listen” to the complex networks that neuroscientists have derived from fMRI scans of 250+ individuals “at rest” in the scanning machine. The ages of the participants are between 20 to 80 years old. The hope is to discern sonic changes in the sounds produced directly from the data, in various ways, and to use this tool to unravel the complex “hairball” that comes with the visuals of most complex networks. This tool in this case will not be used by the neuroscientists, but rather by these musician/composers. They will be performing their sonifications of this data.

There are a variety of sonification methods to use to explore the information with the data stethoscope. A scheme has been devised to combine the various approaches of all collaborators in one unified performance gesture. We have come up with an interesting way of interacting with various data stethoscope sonifications that looks forward while looking back to the original 9 evenings. We take our inspiration from “Reunion” (1968) a piece proposed by John Cage with a special chess board designed and built by Lowell Cross. This new approach to performance led to the landmark event that Cage arranged with Marcel Duchamp at the last months of Duchamp’s life.²

Just as in the original Reunion, we propose using an electronic chessboard as a way of signaling our singular performance moments and our collaborative duos and trios. Each move represents a musical piece that will be credited and worked out separately by the performers, so that each chess move would represent an opportunity to perform a new solo, duo or trio composed by one of the trio.

In the interest of collaborative equality and to help with our planning, we are eschewing the indeterminacy attendant on playing a live game and are preparing the work around the moves of a previous chess match.

- Andrew Blanton will be playing his percussion trigger navigation software that allows his use of his skills as a percussionist to maneuver through the model and data sonifications in this unique way.
- Tim Perkis has developed a system tightly tied to a specific MIDI control knob and button box that equally allows him to maneuver and interact with both the model and the various sonification algorithms we have developed.
- Scot Gresham-Lancaster will be using a guitar midi control system of his own devising that utilized a third way of maneuvering through the model and the associated sonifications of the data.

All of our playing will be done using the multimodal representation tool we have been developing as part of a funded research grant that is regarding investigating signification of network data derived from fMRI scans. So an organizing principle of the performance will involve similar performances on the electroacoustic instruments we have designed, but with the data from different age groups as the data set.

² Cross, Lowell. “Reunion: John Cage, Marcel Duchamp, Electronic Music and Chess.” *Leonardo Music Journal*, vol. 9, 1999, pp. 35–42., doi:10.1162/096112199750316785.

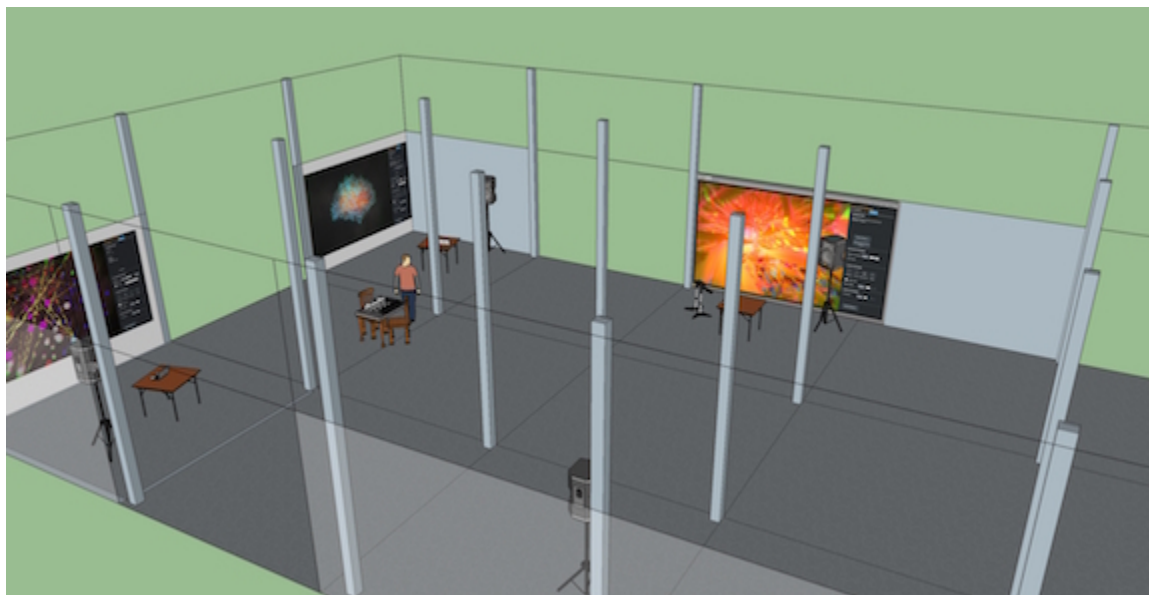
The performance is envisioned in a surround the audience context, but we have some flexibility in that regard.(Illustration 1) Each of the three performers has a speaker near them and their sound can be panned to fan out from that position to the other three channels. So a minimum 8x4x2 professional quality mixer. We will require 4 high definition 1084p 3800+ lumen video projectors with a screen or screens large enough to accommodate the three separate images for the performer's instruments and one for the chess game in progress.

Next are the changes in approach that lead to a less data integrated performance and towards a more independent set of three individual performances

Of core interest here is the way in which the idealized vision of the performance was changed to accommodate the ongoing reinterpretation of the material and context as experienced by each of the individual artists, as they prepared to have each of their respective approaches to handling the data to sound transformation process in their own, very individualistic set of technical contexts towards the material that they were each working with. What follows is a log of the documents that were presented to the event organizers as the approach to the specific ways in which the material would be performed evolved as the context itself evolved.

Once okayed by the concert organizers the more concrete planning began

The dates and location were set, the layout of the venue was communicated to the artists and a plan was put in place for the set up of each of the three performer in the gallery space that was being provided in the top floor of the King St. Rail station in downtown Seattle. Here is a rendering from sketchup of the initial setup in that space



Here is the text as presented to the 9e2 organizers during planning for the performance date:

This performance is based around a “data stethoscope” approach to investigating the use of sonification, or the conversion of data into sound, to “listen” to the complex networks that neuroscientists have derived

from fMRI scans of 250+ individuals “at rest” in the scanning machine. The ages of the participants are between 20 to 80 years old. The hope is to discern sonic changes in the sounds produced directly from the data, in various ways, and to use this tool to unravel the complex “hairball” that comes with the visuals of most complex networks. This tool in this case will not be used by the neuroscientists, but rather by these musician/composers. They will be performing their sonifications of this data.

There are a variety of sonification methods to use to explore the information with the data stethoscope. A scheme has been devised to combine the various approaches of all collaborators in one unified performance gesture. We, as an Art/Science research collective, have come up with an interesting way of interacting with various data sonifications that looks forward while looking back to the original 9 evenings. We take our inspiration from “Reunion” (1968) a piece proposed by John Cage with a special chess board designed and built by Lowell Cross. This new approach to performance led to the landmark event that Cage arranged with Marcel Duchamp at the last months of Duchamp's life.

We begin solo performances of unique nature to expose our approach to using this neuroscience research to discover new avenues for live electroacoustic expression. Then as in the original Reunion, we end up using an electronic chessboard. By the end of the evening we will be using this chess game play as a way of signaling our unique performance moments and in collaborative live duos and trios.

Specifics of each section of the performance:

- Lily Pads (Tim Perkis, 2016) The fMRI brain data we used in this project can be thought of as something like a 441-track tape recording of the level of activity over time at various points in the brain. Researchers consider points in the brain which have very similar simultaneous "signals", or sequences of activity, to be strongly connected, and try to find overall patterns in this network of similarities. Tim Perkis is presenting a simplified alternative visualization/sonification of this brain network data, identifying sub-nets of similarity by taking a wandering journey, following a path among nodes that are strongly connected to each other, "jumping from lily-pad to lily-pad".

- Andrew Blanton will be playing percussion that activates individual connections as well as macro level groupings of connections to extract sonic and visual material out of human connectome data. Working with software that has been developed over the course of the last two years, his software interprets drum audio data and controls realtime audio visual software to act as an accompaniment figure to his drums. Working at the fringes of classical music and New Media Art, his electro acoustic composition practice builds on the work of composers such as Iannis Xenakis, Karlheinz Stockhausen, and John Cage, an artist whose original Nine Evenings' performances helped boost the event to legendary status.

- Scot Gresham-Lancaster will be using a scripted interactive set of midi control systems that are made from various sonification software modules that the neuroscience team has been testing over the course of our research into supplementing visual representations of their data with sound. As an ambient background to this script of procedural interactions with the model, Roger Malina and Gagan Wig will be playing a game of chess on an electronic chess board that moves the camera view in the visual software of the tool the team has developed. Associated with the position of the camera is a sample playback engine that combines various environmental sounds chosen to represent each of the 10 major connectome

systems identified in the research effort associated with this project. This creates an ambient backdrop for the other processes that are being played, all in real time. At a moment near the end of this presentation Perkis and Blanton will reenter the representational environment and interact dynamically with the visual and sound field that these sets of processes have created.

All of our playing will be done using the multimodal representation tool we have been developing as part of our ongoing research. This research is regarding investigating sonification of network data derived from fMRI scans. So an organizing principle of the performance will involve similar performances on the electroacoustic instruments we have designed, but with the data from different age groups and individuals as the source data set.

Actual Performance text:

Below is a shot of the final performance setup in the space. The percussion station was moved to the left corner, the chess oriented controller was moved to the center of the back wall and the Processing based rendition was moved to the far right corner. This created a more “proscenium” style performance area that helped focus the audience’s attention to each of the three movements of the suite as it unfolded.



Here is the description of the various renditions of the data for the actual performance:

Tim Perkis

Lily Pads (Tim Perkis, 2016) The fMRI brain data we used in this project can be thought of as something like a 441-track tape recording of the level of activity over time at various points in the brain. Researchers consider points in the brain which have very similar simultaneous "signals", or sequences of activity to be strongly connected, and try to find overall patterns in this network of similarities. I presented in Seattle a simplified alternative visualization/sonification of this brain network data, identifying sub-nets of similarity by taking a wandering journey, following a path among nodes that are strongly connected to each other, "jumping from lily-pad to lily-pad". The visualization was based on preliminary work done in threejs/javascript before the DARPA-funded part of the project began, ported and elaborated using Processing, a java-based graphic programming toolkit.

The only data made available to us (the artists on this project) was a matrix of the measured similarity between each of these 441 points, and as such did not contain any information about the nature of each node's activity itself. As a consequence, creating a sonification or sound signature for the individual nodal areas of the brain was impossible. So for this performance the sonification is a purely imaginative concoction, made of recordings of sighing refrigeration systems, exhaust fans, frying hamburgers, rustling

forest leaves and of course some purely electronic synthesized sounds, mixed and processed by a parametric model to create what one hopes are plausible nodal and node-group sound events. Sound programming was done in the open-source PureData graphical audio processing language.

Andrew Blanton

For the performance, Andrew Blanton worked with a modified version of the StethoViz software using the nodes and connected regions of the brain as a resonant chamber for drums. This was technically achieved by using a custom PureData patch that acted as an extension of the StethoViz software. This process is an effective strategy for the unique requirements of the live performance environment. Because Unity is a game engine, it has a vast tool set for interfacing with outside data controller input. And PureData is also very robust at sending data at audio sample rate. The overall signal path for the performance was to start with a drum strike on custom drums that were individually mic'd with piezo elements. That audio data was sent into a MOTU 896 mk3 where live peak detection was performed on the six drums simultaneously. Once that peak detection data was into the software, that data could drive both the sonification and visualizations, all in real time.

The sonification was produced by taking that initial peak detection and triggering a query to the custom nodes_meta object. The data that was then returned from the object then drove multiple custom software synthesizers. The synthesizers used were combinations of low-frequency envelopes, banded waveguide synthesizers, and pure sine tone all driven by the weight of the connection. This same node would be visualized in real time with the corresponding sound. Each edge and node in the model had to be sonified and visualized individually, so in order to get the impression of, for instance, a single drum strike the nodes were sonified and visualized as fast as possible in order to create that impression, which was both fast and accurate.

The overall visuals were monochromatic resulting in a more scientific looking representation of the data in reference to the initial 9 evenings as well as the use of pure sine tone referencing the synthesizer sonic language of the mid-century. The intent from the beginning was to construct a system that could visualize and sonify the data in real time and that process was successful. Interestingly in this process, each node must be rendered in real time, but another possible path would be to pre-render each of systems as 3D objects and call those objects through the visualization engine, this would allow for a higher fidelity of the connected regions showing 3D positioning of the edges as well as edge weight. The current software can only show 3D positioning of the edges.

Scot Gresham-Lancaster

Earlier in my career I had the opportunity to work closely with composer/performers John Cage and David Tudor. It was John Cage that connected me with Lowell Cross, who designed the photoelectric enabled chess board that was an important part of the “Reunion” electro-acoustically enhanced chess match between Cage and Marcel Duchamp. I received the circuit for this chess board from Mr. Cross and built a working version of the board for a reenactment of the piece for a celebration of Cage’s work at a memorial concert at Mills College in Oakland, CA in 1998. This cemented my interest in using chess play as a source of indeterminacy as a Post-Cage style musical performance organizing principle.

Fast forward some years later and we are working with the Art/Science lab and the Center for Vital Longevity at UTD and discover that the university has a world class chess program with full scholarships and several World Grand Masters. That program also has a new generation of digital chess boards that can be used to digitally communicate the moves of a chess game in real time. The opportunity arose to use the Art part of our Art/Science collaboration presented itself with an invitation for us to participate in the 50th Anniversary of the historic Engineering Art and Technology (EAT) 9 evening's performance. This time in Seattle and entitled 9E2. This is a wonderful opportunity for us to show our work and dedication to really fully playing at the Art/Science boundary.

The Artists on the team are seasoned performers with decades of experience but the thought occurred to us that we could integrate the symbolic representation of brain activity, the chess game, as a way to get the scientists on the project directly involved in the performance itself. So while we are using a good part of the evening to directly create music using the tools we have been developing to research by visualizing and sonifying fMRI and EEG data in many different ways. Some of these techniques proved useful for the scientists, but all were created with an idea that they would be part of a human experience and therefore be crafted to bear some artistic interest. By the end of the evening the scientists themselves are driving the form of the visual and sonic interactions directly from the chess moves they are making. The symbolic meeting of the minds driving the multi sensory experience the audience is witnessing.

Why show these three iterations of the same pieces?

These three evolving descriptions of the pieces, as proposed, as refined and as realized give the reader an opportunity to begin to understand the dynamic process that goes into the organization of the creative act associated with making new work of this nature. The initial proposal must be envisioned to be within the scope of the skill set, budget and other resources of the participants but still flexible enough to be edited as the piece approaches realization. Once it became clear that the geographic dislocation of the three participants ruled out the ability for there to be real time dynamic network interaction between the players, the topography and sequence of the work was rearranged. This serendipitously resulted in an exhibition performance that highlighted three very distinct approaches to using the same set of data for three very different types of performance. This ended up accentuating the differences in perspective shared by all the performer/composers.

Further Analysis

While these texts are vaguely repetitious, there are distinct transitions toward the final definition of the piece. The cultural memory embodied in a recreation of the 1968 Reunion piece with Cage and Duchamp playing chess reframed the context of the entire piece, pulling it away from the more dogmatic focus of the "pure science" frame that was the original context. This opened up the idea for all three artists to examine their own personal relationship with the material at hand. Initially we had conceived of doing a variation on the decades of work that Perkis and Gresham-Lancaster had done in the context of computer network music with the "The Hub" (reference). The conception supported the idea of representing the data as complex networks using actual complex musical networks as the audio source. This requires some tight coordination across a local internet connection so participants can trade information regarding what

and when to play by way of the agreed upon internet signalling. This is a complex process to establish the connection and then to coordinate a musically substantial reaction to that shared signalling system. The months leading up to the performance date the three performers were geographically isolated from each other and it was determined that there would not be enough of an opportunity to get together and work out the many problems associated with bringing a new computer network music piece to the level of performance. It was decided that each individual would perform as soloists, each performing their own interpretation of the data provided by the neuroscience lab. At first, this was a mildly disappointing, but in hindsight it afforded a unique opportunity to experience three very unique perspectives on the ideas associated with turning raw data into performative sound.

Another interesting aspect of the evolution of the planning for this performance was that by the time of the performance only one of the performers was actually strictly using the tool as it was designed for use in the neuroscience lab. Making a performance using digital resources is a new type of performance planning strategy. Those that do it are used to customizing software in preparation for performance can easily identify what happened in the context of this performance. It is the nature of this sort of work to refine the execution of the software “sketch” that is initially established to shape it into a manageable new instrument. These work habits cut in, to the point that Tim Perkis worked off an entirely different visual representation environment, Processing and not the Unity software that the actual “data stethoscope” exists in. Andrew Blanton took the Unity software instance that the tool was designed in and created his own “scene” that utilized some of the base code, but was highly modified to handle the Open Sound Control (OSC) drum triggers that were the basis of his performance context. This is absolutely understandable in the sense that in order to wrangle software into a context that enables a performer to perform in a meaningful way. The “ask” of using an instrument designed specifically to enable neuroscience research as a performance instrument was a difficult one. A big reason that Gresham-Lancaster was able to meet this requirement was that he was geographically near the lab and had the opportunity to work on a weekly basis with the neuroscience team and associated visual software designers. This was an important discovery that, while we live in a time of easy telecommunication, email etc. it was really necessary over the course of developing the instrument for both purposes to have close, in person, face to face meetings regarding the specifics of what was needed in both cases. Often, during work sessions, “features” that had been added to augment the expressivity of the tool, as a performative set of software, had to be disabled to assure the neuroscience team they were directly experiencing the raw qualities of the data being examined and not an artifact of a performative “enhancement”.

This dilemma of function versus real artistic force, in both visualization and sonification is one of the core knotty problems of this area of research. On his site regarding the symposium in October of 2017, *Transpositions: Science to Art (and back)*³, Gerhard Ecke says:

"At present, scientists use a variety of sonification and visualization procedures to analyse and communicate their findings. For artists, those representations are often of little artistic value since they are geared towards a transparent communication of the data creating little space for artistic interventions. Conversely, by foregrounding aesthetic effects, the expanding field of artistic data sonification and visualization runs the risk of producing art works that only superficially related back to the scientific research from which the data originated. While giving the arts an important role in the communication of

³ Viewed April 2018 <https://www.researchcatalogue.net/view/94538/94539>

scientific activity, the artistic exploration of scientific data may thus add very little to the research itself. Given the ever-increasing amount and importance of data representations, it is of particular importance that artists become engaged with their fabrication and to identify how in spite of their very different constitution aesthetic and epistemic research aims may support each other.”

Our experiences in art/science collaboration have exposed this set of problems in repeated ways between many of the actors in the scenario. The communication of just the form of data to be worked with is often highly filtered by scientist before the handoff to the artistic practitioner. The scientists often have specific results that they are anticipating relative to the very specific aspect of their discipline that they are actively investigating. For them to set aside time and even gamble on new ways of looking at the data in unassured new ways is fraught with concern and an instinct to control the trajectory of the artist’s work, much in the same way that a scientist expects lab assistants to follow the strict procedures of experimental processes. Artists, on the other hand, are bending the perspective and do not have the preconceived notion of a specific result relative to the data set. In the instance of the data set associated with this performance, the neuroscience team wanted cognitive auditory proof that the change in connections from within and between neurological systems changed in a consistent way that supported their previous findings. These results were derived from sifting through the Blood Oxygen Level Detection (BOLD) data that the fMRI scans of the various age groups provided. For example, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3849338/figure/F1/> For the detailed analysis of known clinically determined neurological systems and to track the interconnections this level of “data scrubbing” is absolutely necessary, especially in the context of creating a visual model in the form of a graph, circos diagram or 3d node-edge model often used to depict complex networks visually. However, it is circumscribed to meet the known requirements of these visual and numerical representations. If the intention is to try and hear these phenomenon as time series progressions of change, the data manipulation process might need to be altered to meet the expectations of this new auditory context. A point of contention arose when one of the artist made a request for the “raw BOLD data” which was roundly rejected by the scientists on the team who had spent months getting this raw information preprocessed and filtered through an elaborate set of mathematical transformations to get it to the point where the linkage between the distinct neurological systems was in a state that could be reasonably analysed using modern complex network analysis techniques.

Granted, there was a level of naivete on the part of the artists in this context since they had read these articles and had discussions almost purely at an interested dilettante level. However, there was certainly some merit in working with the artist to understand their instinct relative to trying to investigate if there were primitive audio traces of the connections between these identified neurological systems in a less filtered and more general representation of the complex network derived from the evidence of BOLD interconnections. To be clear, the task was to make a “Data Stethoscope” , so the artistic intuition was to find that place in the time series transformation where the connections would be the raw state of blood oxygen transfer between the visual neural system and the auditory, for example. This could have been a fully flawed approach to creating a usable sonification, but the only way to confirm that, was to try and to fail. The opportunity to fail was never provided. This points to a sort of hard to characterize chauvinism that scientists often inflict on art/science collaborations. This is understandable consequence of the very different nature of tool building in science as compared to new media art performance. One is the result of decades of refined incremental steps towards extremely well defined goals, while the other is absolutely

wide open and experimental in the broadest sense, where the only guiding factor is confidence in the craft required to follow an intuitive hunch that something will fall within the frame of audio that will be generally perceived by the artist (and hopefully others) as engaging aesthetically and even emotionally. If it is information laden, that is an extra bonus.

New media artist Gail Wight lightly touches on this aspect of art science practice with her statement ““Scientists tend to build a lot of checks and balances into their own practice,” Wight said. “But when the information comes to us (artists), we don’t have the same checks and balances.” Wight had engaged in a core questioning of the autonomous veracity of the scientific perspective. As a curator said of her work ““challenge our perceptions and remind us that scientific revolutions have most often arisen when someone has come to see the same object in a new way,”⁴ The unfulfilled promise of an examination of the perspectives of a given inquiry are the strength of the art science collaborative process, but once inside the rigors of these sorts of projects this problem arises repeatedly. The scientists judge the proposed use of their research and hold back the full access to the data as they try to mold the results of the artistic enquiry to supplement their own research agenda in some anticipated way. This is not with malicious intent, but rather has to do with the pattern of operation that surrounds the rigor of the scientific method. It is to a large extent subconscious on the part of the information provider.

To circumvent the problem created by this schism in approach all three artists came up with varying approaches. The most blatantly open can be understood by parsing this sentence in Tim Perkis’ artistic statement that accompanied his program notes the night of the performance. To remind the reader, Perkis says “The only data made available to us (the artists on this project) was a matrix of the measured similarity between each of these 441 points, and as such did not contain any information about the nature of each node’s activity itself. So for this performance the sonification is a purely imaginative concoction, made of recordings of sighing refrigeration systems, exhaust fans, frying hamburgers, rustling forest leaves and of course some purely electronic synthesized sounds, mixed and processed by a parametric model to create what one hopes are plausible nodal and node-group sound events.” (Insert photo of Perkis performance shot here) That being said the illumination of the interconnections from the data provided and the illustrative sounds that were used gave a compelling understanding of the nature of the data under analysis to the lay listener. One interesting feature that was missing in the other two renditions was the opening sections that identified the names of the neurological sensory and associative systems that were being displayed. Famous ecological artist Newton Harrison, who was at the performance, commented that this labelling was sorely missed in the later parts of the performance where it was not present. His advice was to create a word based dialog that drove a narrative regarding the interaction so the audience had more of a clue as to what was being represented. These suggestions have been taken to heart for future performances.

Andrew Blanton grappled with the physicality of the data. As a classically trained percussionist who had developed a performance a year earlier in 2015 with a javascript version of the software for Google Paris, he stayed focused on using drums to trigger clusters of neural firings from the data set that was provided. (Insert Photo of Paris gig here) This is not a way in which the neuroscientists would interact with the model in a lab setting, but it did provide an interesting new perspective on how to move around the

⁴ Seen March 2017 <http://news.stanford.edu/pr/2006/pr-wight-120606.html>

model to discover various types of interactions between systems. Because of the nature of that type of interaction, the playing was not so much about the within and between connection strengths between systems, but rather the direct connection of specific nodes to various other nodes in the various systems based on the strength of the interconnection. The harder the velocity of the strike to the drum the more nodes were played. Additionally, since this was a different approach to interacting with the model, Blanton created a new type of rendering in Unity that as derived from the code developed by the Make or Break gaming company that had created the visuals for the tool, but made more efficient and with a different color aesthetic, more greyscale, than the multi hued color scape that the tool utilized.

Scot Gresham-Lancaster used two sets of software. One is the actual tool used by the neuroscience lab. The other set of software interprets the moves on the digital chess board and sonifies them into pandiatonic melodies that reflect the structure of a chess game as it evolves. The decision to create this counterpoint was two fold. The initial inspiration was a conjunction of the opportunity that arose while working at the University of Texas at Dallas that is home for one of only two fully funded scholarship programs for chess. The existence of this chess program presented the opportunity to get access the the DGT electronic chessboard that is used in the various chess tournaments. Gresham-Lancaster had previously built a version of Lowell Cross' design of a photo-optical mixer designed and used in 1968 for the piece Reunion which was an electro acoustic chess game performed between John Cage and Marcel Duchamp. Since the 9E2 event in Seattle was a looking forward while looking back sort of curation, it seemed appropriate to integrate this technique. Additionally, there is some sort of narrative/zeitgeist regarding chess and the brain that lent itself to the imaginative context of neuroscience and performance that was being created. Secondly, the software tool, the "data stethoscope" required a certain amount of hands on prodding and investigation to get to areas of the various acoustic models that would be regarded as musically interesting in a performance context. These lulls between sonically interesting areas of the sonified complex network are an interesting artifact of the tool, but necessarily left the need for the spaces between these "areas of interest" that needed to be traversed while the tool was being used in real time to be covered by some background texture. That is where the pandiatonic bed created by the ongoing chess game acted as a counterpoint to the sparser sonic areas that were a characteristic of live performance on the data stethoscope tool. Since this was the last piece on the program, it was decided that both Perkis and Blanton would join in with their data interpretation sonifications to supplement the two layers of sonic activity being created by Gresham-Lancaster. This all culminated in a sudden fade when the final checkmate was executed at the end of the chess game which was played by two of the collaborators on the project, Astrophysicist and Art/Science expert Roger Malina and Neuroscientist Gagan Wig.

Conclusions

This has quite possibly been one of the most complex, thorough and yet to be completed multifaceted research project into the current state of sonification, it's relationship to visualization and the deeper and more abiding concept of multimodal representation of data. The technology of the early 21st century has enabled researchers to begin to think in terms of a reintegration of sight and sound, creating a technological representation that begins to approach the actual experience of reality. The act of creation associated with putting a public performance together with these disparate elements of neuroscience and new media performance forced the participants to think outside of their silos. This is the beauty of the Art/Science collaboration process. The lessons learned are sometimes harsh and unnerving as was the

case in the deliberate embargoing of data to direct the creative flow of the artists. This characterizes an ongoing issue of these types of collaboration and points up an interesting problem for future collaborators to be aware of and to deal with. Also, there were many prototypes of visual and sonic systems that never made it to performance. One interesting aspect of this work that is unique is that at times there are several versions and types of data sonification going on in parallel. This points up an interesting new area of performance/research that has the promise of a rather non-systematic use of data representation that is more ecological in nature and will aid future researchers in finding large types of media environments for both performance and analysis. This was clearly just hinted at with this performance, but the presence of this potential was palpable among the collaborators.

This strange new area of data world creation for both performance and research is emerging from technology that is just now able to support this work. As we move forward and expand this area of investigation the potential for new discoveries and possibly even new performance art contexts is quite evident.

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Appendix 6: DATA Stethoscope Project - Technical Note No 2 by Scot Gresham-Lancaster

Nov 11, 2016 <http://bit.ly/DataStethoscopeTechnicalNote>

DATA Stethoscope Project - Technical Note No 2 by Scot Gresham-Lancaster Nov 11, 2016

University of Texas at Dallas. PI Dr G Wig, Co-PI Dr R Malina

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- (6) Block 13, Abstract (must not exceed the 200 word limitation)

Abstract: In this technical note we describe the specific sonifications types developed for the Data Stethoscope Project. (see Technical Note No 1 for the typology).A two year project, the DATA STETHOSCOPE has led to a codification of sets of techniques and their combinations that are specifically in search of the augmentation of the user experience with the addition of information rich correlated sound. Three basic techniques were used: direct audification, sequential, exformation. Three user application modes were used: pattern source creation, search and discovery and monitoring. We describe detailed software implementation strategies. Some of the lessons learned include the need for training data and training modules, the need for protocol standardisation, development of standardised tool sets. We propose codifying an Event Bus protocol to enable the use of a wider variety of software environments across the broader range of visual and auditory SDKs. This will open up this research to a divergent set for other research teams working in the general area of data representation in complex networks. We found that single sonification strategies in a fixed audio visual environment do not have the synergetic result of allowing users access to multiple visual and auditory representations in the same tool.

- (7) Block 14, Subject Terms Data Sonification , Data Exploration,Data Visualisation, Audification

- (8) Block 15, Number of pages: 17

Description of Sonification Types Developed for the Data Stethoscope Project with Lessons Learned

3 x 3 Table of Sonification Techniques and Classifications

Techniques x Application modes	Pattern Source Creation	Monitoring (Soundscape)	Search and Discovery
Audification	Data as gestalt - the direct sounding of the data. Individual data “packets” or icons of sound shaped by the scaled data	Data as environment - the factory - the forest - electroacoustic space	Data as presence - the combination of sound possibilities driven by interaction and navigation
Sequential	Data as melody or harmonic movement	Data as gesture - a sea of sequences that are experienced as a sound field	Data as music - most common realization (bar chart as melody)
Extrinsic (Exformation)	Data as extrinsic parameter change - freq., pitch, tone	Data as location- familiar material displaced by location and reverb	Data as anomaly - enigmatic sonic configurations that make the familiar, unfamiliar

Introduction

This document was created to step through each of the various sonifications that were developed in the course of this research and discuss the functionality of each realization and how that realization relates to the “Technical Document” that outlines the underlying conceptual model that drove the design process for each of the many sonification techniques that were developed. At the top of this article is a copy of the 3x3 matrix that we used to define the focus of our various sonification realizations as we began to try to systematically determine the strengths and weaknesses of each of these approaches.

Three basic Techniques -

Direct Audification, direct unanalyzed mapping of data to sound. In most cases the data will be scaled (time and amplitude) and possibly quantized mapping of the raw time series data to sound.

Sequential - a stepping through of a data set on where the quantities of each data parameter are mapped step by step to a specific parameter mapping. One data field = pitch, another = filter setting a third may be mapped to reverb depth, etc. The timing that drives this sequence may or may not be driven by a parameter of the data itself, but in most instances to date it is a steady clock that plays at a musical bpm rate.⁵

Extrinsic (Exformation) - ongoing time series data, most likely music, but could be as simple as pure white noise or speech (podcast or audiobook read aloud) or combinations of all these that do not represent the data at all, but are very familiar to the user. This well recognized signal is then modified by digital signal processing parameters whose range (intensity) and possibly time scale is driven directly by the data set. Parameters would include pitch, timbre, spectrum (simple Low Middle High filtering, auditory location, reverb amount, amplitude modulation, and many other recording engineering parameters that are well known to sound designers and electroacoustic composers.

Three Basic Application Modes

1. Pattern Source Creation
 - a. Sonification as a formal structure for use in an aesthetic process
2. Search and Discovery
 - a. Sonification provides a sonic analogue of some underlying data which can be freely scanned, inspected and searched
3. Monitoring
 - a. Sonification setup to reflect and provide a global “view” of the multivariate state of a complex systems or processes.

⁵ Gaël Dubus , Roberto Bresin. A Systematic Review of Mapping Strategies for the Sonification of Physical Quantities Published: December 17, 2013 <http://dx.doi.org/10.1371/journal.pone.0082491>

Audification with each classification

Data as gestalt: the direct sounding of the data. Individual data “packets” or icons of sound shaped by the scaled data. This is principle is demonstrated with the instrument entitled **directAudificationSineAndTap.pd** (ab) On node rollover, play sound table sequence based on list of connections to the node. The ranking of the connections is sorted by strength and the number for each sound sample is proportional to the distance between each node. Gestalt

Data as environment: ecoSysPolysample.pd (sgl) On node rollover a sound of 10 different animals sounds for each system is played and the neighboring ten nodes with a sample playback of another animal sound if it is in a different system and the same animal sound if it is in the same system of the node that has been rolled over. Additionally, the pitch of the sample being played is pitched lower or higher depending on the “promiscuity” or tight connection to the community that constitutes that system. The higher the pitch the more “promiscuous” the node. The effect gives the listener the impression of moving through neighborhoods of combinations of animal cries and buzzes that represent an acoustic ecology that moves with the successive roll over of nodes through the model.

Data as environment - the factory - the forest - electroacoustic space: ChessOSC.pd (sgl) every move made on an external chess board connected to the system moves the camera to a specific node in the anatomy of the brain. As the camera travels across the interior of the neural “forest” sounds of various birds, frogs, wind in the trees, crickets etc. are triggered. Each sound is congruent to 10 specific connectome systems (visual, default, auditory etc.) and the base pitch of the playback is tied to the “promiscuity” of each node that is near the camera. Promiscuity refers to how much the node is interconnected to within the system it is associated with and how much it reaches outside that system with various links.

Data as presence: drumNodePlayer.pd (sgl) where the combination of sound possibilities driven by interaction and navigation. In this sonification when the camera does a node rollover a distinct rhythm for each node. The rhythm is based on the a drum sounding when a node in the strength sequence is above a threshold that can be adjusted by the user. This allows the user to fine tune the area of interest and with training begin to identify node interconnections that have

similarities and structural groupings of thresholds that are similar between node combinations. These can only be discovered by this process of being aware of the the **Data as a sonic presence**. The drum sound used is different for each brain subsystem, as in visual system = Bass Drum, default system = snare, etc.

Sequential with each classification

Data as melody or harmonic movement: NodeFreqVocalBell.pd (sgl) on node rollover, play a sound for major brain subsystems: a vocal sound for sensory-motor systems, and a bell sound for association systems. Pitch is proportional to ratio of strong intra-system vs. inter-system nodal links.

Data as gesture - a sea of sequences that are experienced as a sound field:

Each of the following is a beginning of a realization of this very common sonification technique, however we found the researchers less interested in using this technique for their specific research into finding differences related to aging.

inout_oohcyn_nabors.pd (trp) On node rollover, play a sound for each of the nearest neighbors (in space) of the node, using a vocal “ooh” sound if neighbor is in the same system as rolled-over node, or a cymbal sound if not.

inout_oohcyn_RO.pd (trp) On node rollover play a sound for each node most strongly linked to rolled-over node, using a vocal “ooh” sound if neighbor is in the same system as rolled-over node, or a cymbal sound if not.

inout_RO.pd (trp) stethoviz should light up links when a node is selected. On rollover of a link, play a “blat” sound if link is to a node in the same system, or a “beep” if it is to a node in another system.

knobNav_oohcym.pd (trp) using a Behringer usb midi controller, select system with buttons, a node with knob #8, then slider to show/hear links to most strongly connected 32 nodes. sounds are vocal “ooh” for in-system, cymbal sound for out of system.

knobNav_pchnoiz.pd (trp) using a Behringer usb midi controller, select system with buttons, a node with knob #8, then slider to show/hear links to most strongly connected 32 nodes. sounds are “beep” for in-system, pitched noise for out of system. Pitch of sounds are proportional to strength of internode link.

Data as music - most common realization (bar chart as melody) This approach is exemplified in the final version of the sonification realization that we did the most extensive testing on we developed an entirely different and complete user guide for those who were using this one we ended up calling **GoodOne4U_gwnsmc1.pd**. In the following section a detailed explanation of this instrument will be provided, but to fill out this category; using the MIDI portion of the playback design there were two modes that exemplified this technique. In the “velocity” mode a massive 20 note chord was played and the loudness or velocity that each of the notes of the chord that were played was directly mapped to the strength or count for the 20 bins of the histogram of strength of network connections. This was a way to hear an entire system or combination of systems played back as the data was being stepped through. In the simplest case this was a 4 step sequence one for each of the 4 cohorts of age from Young Adult to Elder Adult. In another mode this same set of histogram weights was mapped to the pitch, so a 20 note chord of a fixed velocity was played but the pitches reflected the distribution of the “counts” for all 20 bins.

Data as extrinsic parameter change - freq., pitch, tone:

This instrument was really a complex set of several sonification techniques that were crafted to give the researchers the ability to choose different approaches to sounding the data depending on the specific aspect of information they were listening for. In one instance the Histograms, or counts of connections were mapped to for each system as a band of a 20 band equalizer. The center frequency of the bands for this audio frequency equalizer were set to a distribution known in psychoacoustics as the “critical band”. This is roughly equivalent to frequency bandwidth of the "auditory filter" created by the cochlea, the sense organ of hearing within the inner ear. So in this context the data was an extrinsic parameter that was mapped to each of these 20 bands of frequency which were distributed across the most sensitive areas of listening as determined by psychoacoustic research.

Data as location- familiar material displaced by location and reverb:

AmbiBinauralMix.pd (sgl) was the patch that was developed to investigate this rich and virtually untapped area of sonification research. The locational models that were built around the anatomically correct displacement of the 441 nodes and the 10 systems that were made u of those various node groupings was used to present the audio in a binaural context using techniques developed at IRCAM in Paris and an experimental implementation of the SPAT program for locational audio that we collaborated to get access to. Also, there were experiments performed with the TwoBig ears binaural protocol called 3deception.pd. Both were very taxing and the results provided limited insight for your researches initially. This is an area that will be greatly enhanced as the visual and auditory representations move into Augmented and Virtual reality contexts and is an area that needs much more research support.

Data as anomaly - enigmatic sonic configurations that make the familiar, unfamiliar:

GoodOne4U_gwnsmc1.pd in white noise mode with a familiar wav file loaded into the sample playback area and Noise to sample control moved from noise to waveform. This is not an area of listening that the researchers spent a lot of time investigating, but the promise of further research and specifically user listening training will greatly increase the efficacy of this approach.

We discovered that It is complex to get a naive listener to hear the subtle changes to familiar musics, podcasts or other familiar sound sources that are then filtered by the critical band filter bank described before and additionally modified with parameter driven signal processing such as reverb time, acoustic damping, amplitude modulation, phase modulation etc. All of these parameters have very rich and Identifiable sonic qualities that they map onto sound sources that are familiar to the listener, but there is a need for even more extensive training to listen for the changes that this approach to auditory data presents to even the most advanced listener.

It is this aspect of sonic unfamiliarity and the need to train the users as listeners that explains the fact that the various practices of sonification described in the last sections here take a significant commitment by a user/researcher to start to really begin to hear the data in a critical and useful way. This is primarily a cultural problem, in that each individual brings their own experiences in the form of musical training and cultural understanding and accompanying tases

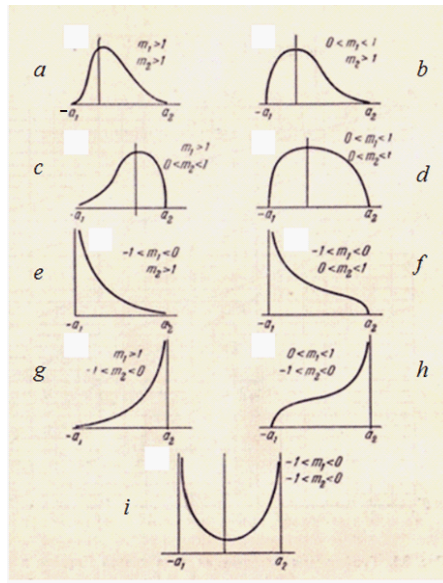
Conclusions regarding the need for training and future research.

The work bringing our experimental instruments into the lab and pushing towards the first phase of a more generalized instrument demonstrates the added value of the sonification for data exploration and comparison for the connectome data set. The complexity of the name of the last instrument that was tested reflects the neuroscience researchers direct editions to the existing instrument at the final stages of testing the instrument for efficacy (i.e. GW = Gagan Wig, NS = Neil Savalia MC = Michela Chan . **GoodOne4U_gwnsmc1.pd** This is a testament to their commitment and involvement with the development of the tool set being created.

Our goal going forward is to develop the tools that will more generally applicable. This future result should meet the shared goal of being able to be used as a “Data Stethoscope” across the field of Network Science and Network Data Analysis. There is a need to create a consistent auditory vocabulary that maintains the subtlety of differences in data and is still familiar enough to be used repeatedly on the data sets and return to the areas of interest in a consistent manner. The literature on medical stethoscopes demonstrates that medical personnel with musical backgrounds, as well as the use of sonic training sets, improves dramatically the ability of medical personnel to detect anomalies through the stethoscope. The problem is accentuated for the data stethoscope because of the large variety of data sets, as compared to the limited number of applications of the medical stethoscope. To extend the use of the data stethoscope beyond the test data sets used for this project, it will require the development of training protocols and test data.

Our experience in testing the many types of sonification techniques that we were examining over the course of this research has led to a conclusion regarding the nature of training that would need to be further examined to more fully understand the efficacy of using sonification as an integrated part of future data representation scenarios. With the following illustration visual standard deviation models of statistical distributions most will be accustomed to understanding what these visual representations in cartesian space imply in terms of the information embedded in a body of data, but what of the sonic equivalent of curves of this type ? A systematic set of training modules need to be more fully developed and tested across a cohort of users to more fully understand the intuitive efficacy of this sort of training.

The subtle differences that we can easily spot visually between figure a,b,c and d will necessarily require a standardized style of sonification or sets of sonifications that will need to be



systematically learned by a user. We did some preliminary tests of this approach to the data that we were examining, specifically using the white noise model with bandpass filters over the critical perceptual auditory bands. This was basically a heuristic test with only 10 or so individuals, but did result in more accurate identification of data types, left and right leaning curves, more or less exponential to linear distribution.

Further development of a generalized multi use sonification instrument that expands on the model of the “GoodOne4U” type which integrated 4 distinct types of sonification techniques in the one tool is the direction that the future

research in this area is headed. In a review of all the various sonification implementations in the literature very few projects expand the sonification instrument under study to more than a single instrument. One major discovery made in this current research is that offering a variety of approaches to examining the data set with various types and technical approaches to sonification have yielded a clarity of understanding not as readily apparent with just a single technique.

It became clear as the final testing was being developed and executed that there were shortcomings in flexibility with the handling of various data sets. Due to the separation of the audio and visual development cycle, two sets of techniques were developed to handle the data set under investigation. With the introduction of each new data set, there was a need to use external scripts, outside the tool itself to message the data to fit these differing formats in the visual and auditory rendition of each new data set. This points to the need for a third spur of development in the more advanced and integrated design that will be part of the next phase of this research which will include a tight integration of standardized data handling across the visual and auditory model being used.

After decades of work in the sonification area by other researchers, it can be clearly concluded that we have broken new ground in understanding the promise and the unexpected challenges of making the much sought after universal tool that would allow any researcher the ability to fold the auditory sense into the research of complex networks with the ease of all the other tools that

have been developed for visual 2d and 3d (with and without motion) representation. We have successfully demonstrated that it is possible to approach this design goal and have discovered the many integrative features that the more generalized tool should encompass.

Virtual Reality (Oculus Rift⁶, HTC VIVE⁷, Google VR daydream⁸ etc. and associated technologies related to augmented reality (Magic Leap⁹, HaloLens¹⁰ etc.) are finally emerging in the marketplace with well designed and thoroughly thought out SDKs that were not available even last year when we began on this phase of the research . Our initial work in Unity¹¹ and using SPAT from IRCAM was in anticipation of a future developments of the data stethoscope class of tools that take advantage of the three dimensional representation availed of these growing technological platforms.

The most tangible result of all this work is the utility of the “Event Bus” which allowed a direct intercommunication between the auditory and visual design and vice versa. Future work will include the standardization of this Open Sound Control protocol as a nomenclature to open the usage of our sonification discoveries across the range of future projects that will be integrating visual and auditory data representation. The advantages of this approach became apparent as we experimented with other visual environments such as Processing, MatLab and Cytoscape and auditory sonifications not only in PD-extended and PDlib, but also Max/MSP, Csound and SuperCollider.

⁶ "Oculus User Guide" (PDF). Static.oculus.com. Retrieved July 17, 2015.

⁷ HTC Vive SteamVR SDK <https://www.htcdev.com/devcenter/opensense-sdk/htc-vive-steamvr-sdk> Retrieved Nov. 2016

⁸ Google VR daydream, <https://vr.google.com/daydream/> Retrieved Nov. 2016

⁹ EmTech Digital, MIT Technology Review. "10 Breakthrough Technologies 2015 - Magic Leap". MIT Technology Review. Retrieved 9 June 2015.

¹⁰ With HoloLens, the future of reality is augmented - pdf phys.org/pdf342432964.pdf retrieved Nov. 2016

¹¹ Technologies, Unity. "Unity - Manual: Unity Manual". Docs.unity3d.com. N.p., 2015. Web. 29 May 2015.

As we inspect the tools available for use in this area of research, Gephi¹², R¹³, Cytoscape¹⁴, NetworkX¹⁵, MatLab¹⁶, SNAP¹⁷ etc. it is clear that the important next phase of this work is to integrate our rich findings in the distributed techniques (the 9 broad areas of sonification outlined above) into the toolsets that are used across disciplines and areas of research that are using complex network analytics as a fundamental part of their analysis techniques.

The next step will involve developing robust applications based on the prototype developed so far, drawing on user experience methodologies being used in the ArtSciLab on other projects. Of specific interest is the concept of extending and refining the training modules associate with each new sonification type that will enable refined and more subtle listening techniques for participating user bases. The need for this sort of auditory orientation became a critical part of getting the researchers on the project to the point of really discovering the efficacy of tools under development and made the actual use of the tools possible. Future work clearly needs to include the development of training modules and practical guides for each sonificaiton that is being used as a “data stethoscope”

We are at an exciting and promising juncture with this work and are looking forward to the next phase where all these lessons learned are brought to bear on a wide range of real world applications and researcher’s various future needs. As the sophistication of data acquisition becomes more complex and extensive, this is a facet of the research is needed to keep up with the boundaries of discovery.

¹² Khokhar, Devangana. Gephi Cookbook: Over 90 Hands-on Recipes to Master the Art of Network Analysis and Visualization with Gephi. , 2015. Internet resource.

¹³ R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.

¹⁴ Shannon P, Markiel A, Ozier O, et al. (2003). "Cytoscape: a software environment for integrated models of biomolecular interaction networks". *Genome Res.* 13 (11): 2498–504

¹⁵ Aric A. Hagberg, Daniel A. Schult and Pieter J. Swart, “Exploring network structure, dynamics, and function using NetworkX”, in *Proceedings of the 7th Python in Science Conference (SciPy2008)*, Gäel Varoquaux, Travis Vaught, and Jarrod Millman (Eds), (Pasadena, CA USA), pp. 11–15, Aug 2008

¹⁶ MathWorks, Inc. MATLAB : the Language of Technical Computing : Computation, Visualization, Programming : Installation Guide for UNIX Version 5. Natwick :Math Works Inc., 1996. Print.

¹⁷ J. Leskovec, J. Kleinberg and C. Faloutsos. *Graphs over Time: Densification Laws, Shrinking Diameters and Possible Explanations*. ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (KDD), 2005.

Appendix A: The more generalized GoodOne4U_gwnsmc1 sonification instrument

A series of sonification instruments were developed that used a technique for accessing data playback for any or all systems in parallel via within/between Histograms driving spectral content.

Here is a rundown of the steps one needs to take to understand and use this particular instrument.

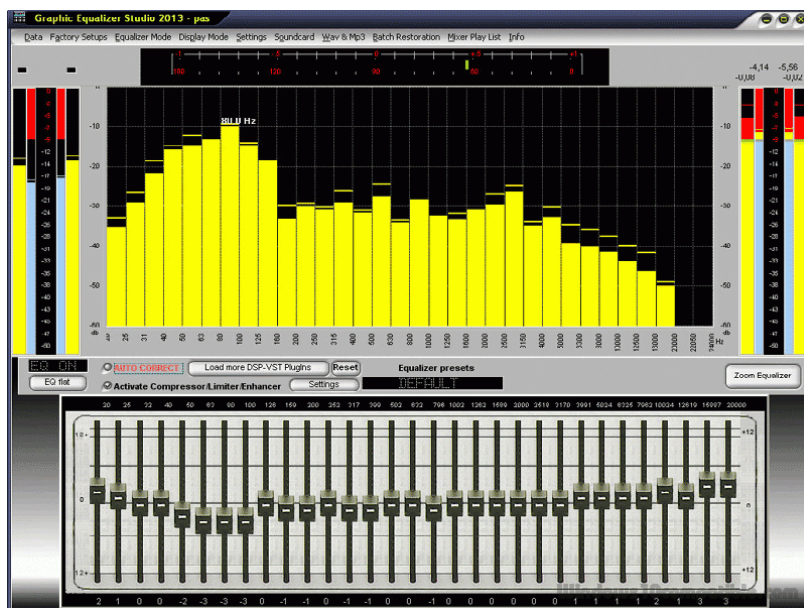
(1)The first process is to take a large data set and have it reduced in representation to a data distribution plot or histogram. This histogram is made of the “count” of connections at each of 20 bins of data strengths. This enables the ability to set threshold and system requests and get immediate responsiveness from the data set.

(2)Next there is a mapping the bins to notes or frequencies (depending on the sonification), with the amplitude of the bin corresponding to velocity of notes of a large 20 note fixed chord, where each note represents a specific one of the Histograms “bins”. As the data set is played back sequentially different notes of the chord heard as each note has a unique amplitude relative to the count associated with the Histogram bin assigned to that note..



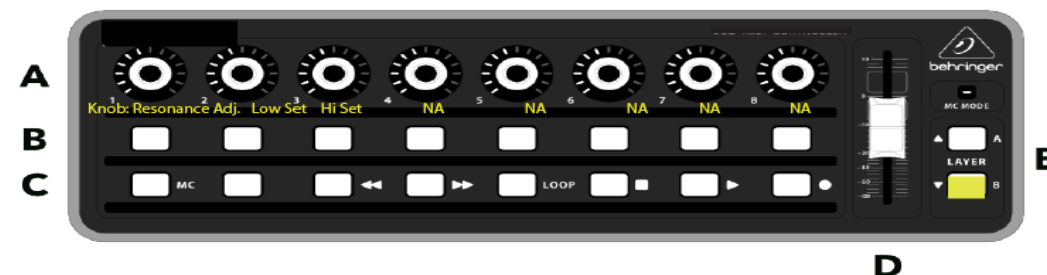
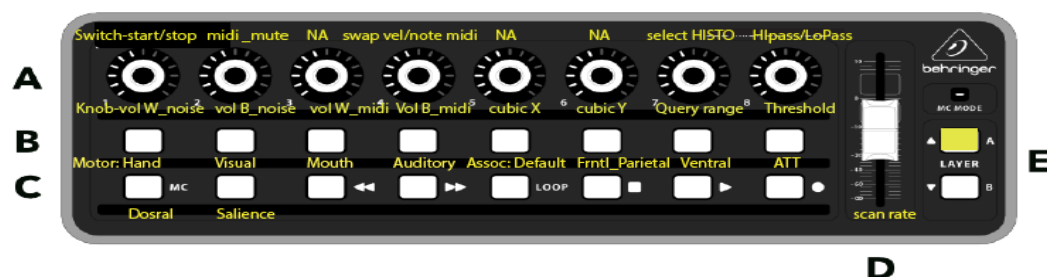
Another mapping is to put noise or music through a filterbank and amplitude of the band in the filter bank that is congruent to the number of the count in each bin of the Histogram.

The filter bank can be thought of as a graphic equalizer that you may see in a car, home stereo system or in some audio software packages as seen in this figure .



if data differs, the shape of the histogram differs and that should be heard if you understand the mapping (e.g., strong values of the histogram [far right] = high notes, weak values of the histogram [far left]=low notes).

Here is the mapping was assigned to a Behringer xtouch mini midi controller (diagram on next page) that we chose to give us real time control of the parameters needed to “fine tune” tune the tools settings, once a data set was properly configured and loaded into the instrument.



This set of controls allows any system to be turned off or on so one can observe each system individually or in any combination to the point where all the systems are activated. Also, there are the first 4 knobs in which knobs 1 & 2 control the volume of the Within and Between systems as noise or filtered file playback and knobs 3 & 4 the overall volume of the MIDI playback associated with the playback of the large chord that is sounding of each bin of the Histogram. With these knobs you can adjust and hear the differing qualities of the area of data under investigation.

To summarize, there are two sonifications that can be listened to together or as separate experiences.

I. MIDI playback with velocity mapped to a single chord

Two Chords are played a fifth apart with a different timbre for each system that is enabled (i.e. Hand = piano, Visual = vibraphone, Auditory = accordion, etc.) The volume of the WITHIN systems are controlled by Knob 3 and the volume of the BETWEEN system are controlled with Knob 4. Once you've figured that out you can play a single data set or a collection

II. Filtered White Noise:

One is a set of filtered noise that represents the amount of connections of the WITHIN connections of the systems that are enabled in the left channel and the BETWEEN systems that are connected in the right channel. One hears the difference in the representation of connections as separate bands of noise that are enabled from high to low in the frequency spectrum. The general volume of the WITHIN systems that are sounding are controlled on Layer A Knob 1 while BETWEEN is controlled by Knob 2. The other critical adjustment for hearing the differences is with knob 8 which adjust the threshold. Additionally, Knob 8 can be depressed to toggle between a state that sweeps the threshold from the bottom to the top of histogram bins or conversely from the top to the bottom of the Histogram bins. This setting also has the option of sounding a wave file to

playback through the filter bank and can be used to investigate the concept of exformation filtering discussed earlier.

The default setting of this instrument is stepping through 4 primary sets of Histograms that represent the information gleaned from 270 + functional Magnetic resonance Scans (fMRI) that were done on a whole cohort of volunteer patients. Each of the 4 groups represents the volunteers at different age ranges (i.e. YA young adult to OA old adult) with about 50 or so in each group (published in Chan, Park, Savalia, Petersen, Wig, *PNAS*, 2014). The information was put through rigorous analysis converted to a representation as a complex interconnected network and those interconnections were derived as the histograms that are being examined with this tool. The Neuroscientists are interested in the changing of connections from WITHIN a given system, so sections of the visual cortex linked to another section of the same visual cortex system) or BETWEEN systems, so from the auditory system to the default association system, etc. These connections change in interesting ways as healthy individuals age and understanding these changes contains rich information about the aging process.

The instrument has additional functionality associated with larger data sets and there are controls to set the start and end of a given data set. This is not really needed for a data set like the 4 cohorts that was the focus of much of the research into the use of this tool. However, there are much larger data sets with possibly thousands of data points instead of just four. So these controls can be used to focus in on specific sections of a large set of data. Instead of stepping through from 1 to 1245 (if the data set was that large) the lower number can be set to 65 the upper to 85 and then a 20 step area of the larger data set will be played back.

Additionally, there is a large fader that sets the overall scan rate. This can be used to quickly scan over a large data set for a general sonic overview and then slow down and really tune in and listen to the details as the playback is slowed down.

Note: This technical note will be revised and finalised for the final report and will be used as the source material for the planned publications.

Appendix 7: Research Review of Taxonomies for Sonification <http://bit.ly/TaxonomyReview>

White Paper: Research Review of Taxonomy for Sonification

February 4, 2019

Author of Document with edit rights: Scot Gresham Lancaster

Co authors with comment rights: Roger Malina, Sharath Chandra Ram

This paper attempts to use a few words to boil down the core idea, characteristics and techniques that have been laid out in the field we are calling LISTENING TO DATA, but often referred to as sonification. This is a collection of pointers to previous work done on refining a full “taxonomy of sonification” or more plainly: how scholars have been trying to define this, as yet, audio based human machine interaction that is not being that used widely, yet.

From: Hermann, Thomas Taxonomy and Definitions for Sonification and Auditory Display ICAD proceedings 2008

Sonification Definition: A technique that uses data as input, and generates sound signals (eventually in response to optional additional excitation or triggering) may be called sonification, if and only if:

(C1) The sound reflects objective properties or relations in the input data.

(C2) The transformation is systematic. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change.

(C3) The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical.

(C4) The system can intentionally be used with different data, and also be used in repetition with the same

From: Nees, M.A., & Walker, B.N. (in press). Auditory interfaces and sonification. In Stephanidis, C. (Ed.), The Universal Access Handbook. New York: CRC Press, pp. 509. (with the addition of pointers to our related research)

Common Auditory Display Classes	Typical Forms or Characteristic Sound Manipulations	Common Functions in Systems	Realized versions in our research
Alarms	Brief, simple, sounds that capture attention	Alerting, warning	
Auditory	Environmental	Object, status, and process	

icons	sounds; ecologically relevant sounds	indicators; auditory menus	
Earcons	Brief, abstract motifs with rule- based iterations	Object, status, and process indicators; auditory menus	
Spearcons	Brief, accelerated speech	Object, status, and process indicators; auditory menus	
Auditory graphs	Data mapped to frequency	Data exploration aids	
Audification	Periodic data sampled within audible range drive frequency	Data exploration aids	
Model- based sonifications	Various	Data exploration aids	
3-D audio displays	Virtual spatial audio via HRTFs	Spatial-orienting cues; navigation aids	
Soundscape s	Various, often naturalistic	Ongoing status indicators; monitoring aids	
Audio in arts and entertainme nt	Various	Sonification as art; aids for enhanced and accessible experiences of exhibitions, games, etc.	

4 classes:

- Soundscape – environment of events that represent multiple parameters that are changing in time, an accurate representation of the state of a multi-parameter complex data set over time (ecological)
- Sequence – a trip through a data set, movement is artificial, NOT from the data (gestural)
- Audification - direct unanalyzed mapping of scaled time series data to sound (gestural)
- Extrinsic - (i.e. exformation) – time series ongoing which does not represent the data, but is modified acoustically, temporally, by the data (ecological)

Each of these 4 classes or sonification types can trigger perceptual alerts, alarms or be perceived as sonic icons: symbolic punctual sonic occurrences representing discrete events.

As of April 3 2014

Unpublished From: Scot Gresham Lancaster, Andrew Blanton, Frank Dufour, Roger Malina
UTDallas ArtSci Lab unpublished internal research document

1. Alerts and Alarms (hunger vs actual pain) (*the boy who cried wolf problem*)
 - a. Alerts warn (Alarm clock is triggered by time) (pay attention to the intention)
 - i. multi dimensional triggering
 - ii. multiple sonic events associated with various trigger types
 - b. Alarms are a call to action (getting out of bed, for example)
 - i. Credit to Samuel Bordreuil for making this distinction
 - c. An Acoustic Ecology can create a standardized space that is “disrupted” by abnormal sonic events that represent displaced data outside the normalized set of sounds created by the combination of material. (More of a note than a C category ...)
2. Audification (vinyl record analogy)
 - a. Direct mapping of (often scaled and massaged data) into sound
 - b. Raw Data dumped to a digital to audio convertor
 - i. Valentina Vuksic: Tripping Through Runtime <http://vimeo.com/4105144>
 - c. Physical manifestation (for example, Richard Lehrman <http://www.west.asu.edu/rlerman/> or grinding a rock across a grate)
3. 1st order sonification
 - a. Cog Sci- UST/ sonic icons...
 - i. earcons <http://sonification.de/handbook/index.php/chapters/chapter14/>
 - ii. UST - “universality?” where and how does the actual segmentation happen?
 - b. Remapping scaled and messaged temporal data flows
 - i. via displacement mapping
 1. quantized (example: major musical scale)
 2. unquantized (example: major musical chromatic)
 - ii. via spectral remapping
 - iii. via temporal scaling and remapping
 - iv. via dynamic scaling of amplitude and temporal location
 - v. Combinations or temporal configurations of all these
 - c. Spawned aural reaction
 - i. Factory metaphor (unstabilized state machine)
 1. Thanks Tim Perkis via Jeff at Interval
 - ii. Nodes as generative machines
 - iii. Temporal change as generator
4. 2nd order sonification
 - a. Exformation driven (User illusion)
 - i. Culturally biased perturbation of “known” audio sources

1. (familiar music or audio get varying amounts of reverb, for example)
- ii. Created familiarity musical or as sound environment that is perturbed by temporally changing data
 1. (establishing a familiarity by repetition then perturbing values in the now familiar new sonic context)
 - 2.
- iii. Metaphor (def Myth relative narrative with changed decision tree)
- iv. metonymy (def representation i.e. crown represents the king)
- b. Visually driven reaction
 - i. biological
 - ii. virtual
 - iii. metaphoric (complex and requires dialog ... semiotics?) going back to Alerts and Alarms
5. Synesthesia (not the pathological definition) (Normal is just the top of the Bell curve)

Gestural - Melodies and Sequences of remapped data and direct "audification" like earlier work with "reading" the data directly

Ecological- soundscapes and "perturbed" prerecorded known musical pieces (exformatic)

Alerts and alarms are a separate phenomenon that can be embedded in either of these contexts. The traditional "alarm clock" metaphor is easily part of the "gestural" class of sequence and audification as these types can have sudden new instances that are triggered by thresholds in time series data streams.

The "ecological" type is more subtle and is dependent on the listener becoming more familiarized with a complex field of sound created by a combination of data driven sound streams mixed together. The classic example is the sound at a country train station when one hears the approach of the distant train horn before it comes into sight. The alarm and/or alert arises from the perception of a change to the overall auditory perceptual environment. This could take the form of a sudden change in one or several of the soundstreams, but it could possibly be the result of an overall change in sound that happens with the combined sonic interaction of all the streams. The expertise of doctors or mechanics with a stethoscope

Other Resources:

<http://sonification.de/handbook/>

Alberto de Campo's dissertation "Science by Ear"

http://albertodecampo.net/uploads/ScienceByEar_diss_deCampo.pdf

Conclusion

These taxonomies are just a way of understanding the audio portion of a larger multi-modal representation. Motivates the exploration of different types of sonification. Ideally we create the physical model of a full object. The fundamental synthesis of visual, auditory and hopefully other senses ... cross modal. This approach opens up the huge research base of cognitive psychology and sensory evaluation are made available.

Also, there is subclasses that were identified above that are for a situation where other activities inhibit the user from looking at a display of information. This could include driving, for example, but really any activity where one must keep looking at something, but would be aided by computer assistance and real time analysis. We have created a new classification and techniques grid that is an extension of the taxonomies identified in this white paper. Please read (INSERT TITLE HERE) to get an understanding of our new work in the area of coordinating types of listening to data for various purposes and use cases.