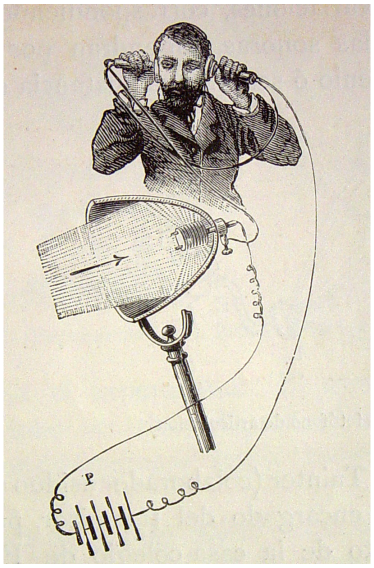
Listening to uncertainty
Exploring statistics through sound

March 1, 2012



> I have heard articulate speech by sunlight! I have heard a ray of the sun laugh and cough and sing!

Alexander Graham Bell, known as the inventor of the telephone, wrote these rapturous words to his father in 1880 describing his newly invented photophone. He was so excited that his wife had to convince him not to name their daughter "Photophone." The device used photosensors connected to a telephone to turn light signals into sound. Its main purpose was to communicate signals by modulating light, but he was intrigued by the idea of applying the technology to study the spectra of stars and sunspots by listening to the sounds produced by the photophone receiver.

Bell was on to something. After all, we use our listening skills all the time for complex analysis and diagnosis tasks. How's the car engine running? Is the wall hollow? Where is that ambulance siren coming from? The Geiger counter, which represents radiation level with audible clicks, remains popular

Box 1: Data's many soundscapes

Sonification is being applied all over the academic world to represent data in a novel way.

Physics A group at CERN, LHCsound, has been exploring high-energy particle collisions from the Large Hadron Collider; NASA has created a tool to sonify the cosmic background radiation in a variety of model universes with different physical constants than ours.

Models and optimization Germany's Bielefeld University, a hub of complex sonification research, has led projects in sonifying machine learning algorithms so that users can more fully interact with neural network models and optimizations as they progress.

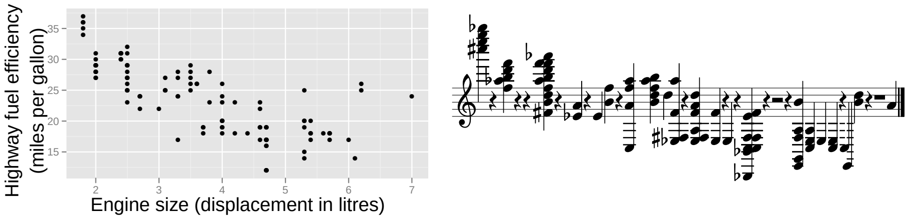
Sport Nina Schaffert, a human movement scientist at the University of Hamburg, leads research on training elite rowers by sonifying their acceleration. This gives rowers real-time feedback without a distracting visual display.

Public exhibits The "Walk on the Sun" exhibit from Design Rhythmics Sonification Lab invites people to walk over the sun's image, triggering synthesizers that sonify solar data based on their positions. University of California at Santa Barbara exhibited "The Allobrain" recently, an interactive and multimedia virtual-reality world created from fMRI data.

a century after its invention. We process auditory information differently than visual information–sometimes in ways that are fruitful for gaining new insight. Our brains can distinguish pitch, timbre, rhythm, loudness, spatial location, and complex timbres with incredible resolution in time.

Yet our exploratory data analysis remains eerily silent. The emerging field of sonification, the audio equivalent of visualization, explores the opportunities for using our powerful auditory sense to understand the world's variation and uncertainty. The history of data visualization is filled with familiar examples of innovative data representations that inspired new discoveries. But vision isn't always an option, which is why NASA's MathTrax software sonifies functions and datasets for math/science students with vision disabilities. And a growing body of research from Georgia Tech's Sonification Lab, Bielefeld University's Ambient Intelligence Group, and elsewhere has demonstrated and evaluated a variety of sonification displays with the potential to enhance the way we think about data and models (see Box 1).

We here give a taste of these promising and exciting techniques. Sonification can be used to communicate the general shape and structure of a dataset via audio scatterplots and boxplots, explore complex structures in time series with audification, and create virtual sound models of data for analysis and presentation. Finally, we describe an interactive GIS application that uses vision and audio together to exploring the uncertainty around projected climate predictions in the United Kingdom.[1]



(a) Visualization (b) Sonification

Figure 1: Fuel efficiency of selected U.S. cars in 2008 by engine size

Hearing the data's shape

Most visualizations take variables in a dataset and represent them via visual parameters such as position and colour. It's the same idea with sonification: data variables are represented by audio parameters such as timing and pitch.

Let's look at a simple visualization: a scatterplot of miles per gallon and engine size of popular U.S. cars in 2008 (Figure 1a). Engine size is represented by horizontal position and miles per gallon is represented by vertical position. We can see a downward trend, though the data forms a wide band and on the right there are several relatively fuel-efficient cars with large engines.

For our sonification, we represent size via timing and miles per gallon by pitch, forming a sort of data song (Figure 1b, sound at `soundcloud.com/tnt-yow/fuel-efficiency-via-marimba`). This audio scatterplot is completely analogous to the visual one, with each note representing a car model just as points do in Figure 1a. The same trend is audible in the sonification, where one can hear a thick descending cascade with several stray high notes right at the end–those large-engined fuel-efficient cars that we see above.

Time series as a waveform

A recorded audio sample is nothing more than a time series of sound pressure levels; computer speakers then vibrate to produce the compressions and rarefactions of air that we hear as sound. What if we went the other way–started with a time series and played it as if it were a recorded sound? This technique, called audification, is in fact useful for exploring long time series datasets.

This should be no great surprise. Statistical time series analysis and audio signal processing theory are based on the same mathematical machinery, and concepts that are useful for shaping sounds are the same techniques that are used to understand time series.

For instance, let's examine a basic time series process, an autoregression of the second order. Here ε_t is normally-distributed white noise:

$$X_t = 0.6165X_{t-1} - 0.995X_{t-2} + \varepsilon_t$$

We could graph this process but it just looks like a dense mat of points. The structure, however, becomes immediately apparent upon audification. Here, we can listen to this data by picking a small unit of time (such as a 10,000th of a second) and interpret the time series as a sequence of sound pressure levels that a computer can play (sound available at `soundcloud.com/tnt-yow/fuzz`).

When listening, it's immediately audible that there is a persistent pitched tone. Musical pitches are in fact periodic components of sound, so we're hearing that the time series has a periodic component.

Visually this could be also distinguished by using a spectrogram or periodogram. But some real datasets are already sound-like and it can be useful to hear to understand their structure. For instance, some processes are either already sound but inaudible to the human ear (bat calls), or are mechanical vibrations that act like sounds (heartbeats that we listen to by using a stethoscope). The audification process takes these sound-like datasets and turns them into sound that we can interpret using our well-adapted ability to determine aspects of natural vibrations, as opposed to the unnatural (if more musical) techniques described in the audio scatterplot example above.

Audification is by far the oldest member of the sonification family, and not just because of the stethoscope. Researchers in 1878 analyzed the frequencies of muscle cell reactions using the recently-invented telephone technology; and earthquake researchers have listened to the fascinating sounds of an audified seismograph since the 1960s (example at `sonification.de/handbook/media/chapter12/SHB-S12.3.mp3`).

Playing data like a fiddle

These approaches to sonification are the easiest to explain, but they may not be the easiest to use. A disadvantage of these particular displays is that non-interactive auditory scatterplots or audifications present just one scan of the data and are hard to get more information out of.

Model-based sonifications, pioneered by Thomas Hermann at Bielefield University, address this by creating interactive virtual models out of each dataset. The user then explores the dataset by exciting it in various ways, like wiggling the mouse in a certain area or deforming a special foam controller. The entire dataset becomes an instrument. For instance, the "data sonogram" allows users to click at various points which send out shock wave that causes audible interactions with the data in a model space. These promising techniques are still quite experimental and need more user testing to see what designs, if any, can help people think statistically about data represented by these abstract sound models.

Simpler forms of interactivity are also possible; the GIS application presented below still give listeners control over where they are in the dataset while providing a straightforward strategy for exploring spatial data through vision and sound.

Sonification in action: mapping climate change uncertainty

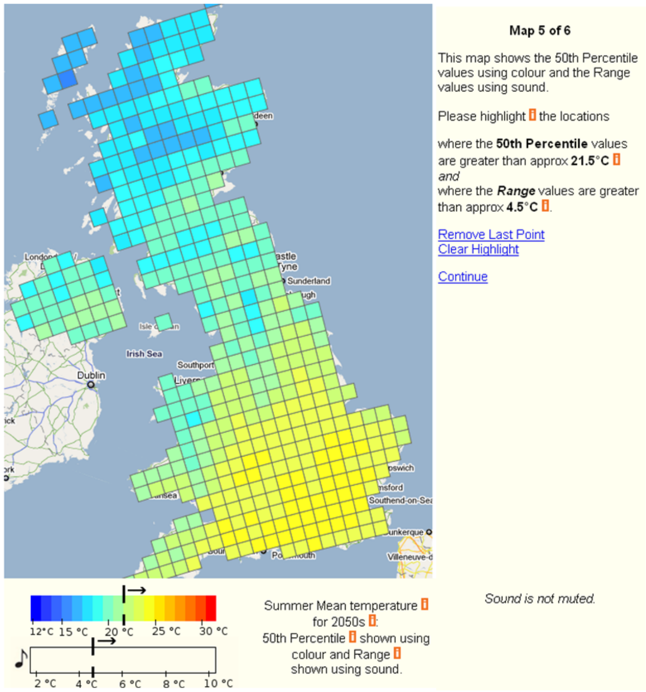
Climate science stirs many debates, not least because of the uncertainty of climate projections. Reto Knutti's *Significance* article in 2008 discusses how uncertainty is an inherent aspect of any climate model, because we do not have perfect knowledge about the processes we are trying to understand. We have to make parametrizations and assumptions, based on our current knowledge.

The UK is leading the way in communicating this uncertainty to practical users by publishing a modeled uncertainty distribution around each projected temperature in its UK Climate Projections 2009 (UKCP09).[2] These projected temperatures are a complex amalgam of many different climate models, weighted by models' success at matching currently known information.

UKCP09 presents temperature change percentiles of a cumulative distribution function for different UK regions. To get the predicted probability for a temperature range, then, one takes the difference between the percentiles. For instance, someone building an industrial plant in Eastern Scotland may decide they want to be 80 percent certain that climate change in 2050 is in a certain range (based on a "medium" emissions scenario). Their temperature range, then, would be from the 10th percentile (1.2°C) to the 90th (3.1°C).

While having this uncertainty model is very useful for accommodating different risk tolerances, it is still a challenge to represent effectively. One could represent spatial data (such as the predicted future climate) using a 2D map, with blues for lower temperature increases and reds for higher temperature increases. However, how can we represent this extra uncertainty information? We could show the temperature with colour, as before, and the range with some type of hatching or shading, but this could easily obscure the underlying temperature data. An alternative to this is to use sound and create a computer-based map. In Figure 2, a Google Maps interface shows the temperature visually, and an added sonification layer displays the range between the 90th and 10th percentiles with higher notes (generated by a computerized trumpet sound) representing wider uncertainty ranges as the user moves their mouse over the map. Using an interactive method to explore spatial data is not new, but applying the technique of sonification to it is relatively unexplored. You can see an video example of this at `http://vimeo.com/17029358`.

While this sonification seems to represent the information we want it to, is it actually any use for the people who use this information to make decisions? Eighty-two users were asked to do some spatial tasks with the sonification interface and give feedback on how useful and helpful they thought it was. The evaluation consisted of a series of projected future temperatures for the UK, shown with colour representing median temperature and sound representing



Map 5 of 6

This map shows the 50th Percentile values using colour and the Range values using sound.

Please highlight ℹ the locations

where the **50th Percentile** values are greater than approx **21.5°C** ℹ
and
where the ***Range*** values are greater than approx **4.5°C** ℹ.

Remove Last Point
Clear Highlight

Continue

Summer Mean temperature ℹ
for 2050s ℹ:
50th Percentile ℹ shown using
colour and Range ℹ
shown using sound.

Sound is not muted.

Figure 2: The interface for exploring UK Climate Projections 2009. Blues represent lower temperature increases while red represents higher. Tones representing the size of the uncertainty range are played as the user hovers their mouse over an area.

uncertainty. The users were asked to highlight the areas that exceeded a specific threshold, where the projected future temperature is above 3.4°C and the range is above 4.0°C.

A sizable proportion of the users had experience using GIS, and some of this group found the sonification a struggle to use because it was so different than the visual methods they were used to. Equally, some of the participants who used the data on a regular basis found the sonification a very useful way of presenting the data because it made the uncertainty element more accessible. This phenomena has been seen in sonification studies before, but there was no clear indication what was different about the two groups of people; in agreement with other research, musical ability and learning preferences do not explain the variation.

The interactive element of this sonification was very important to its relative success; a non-interactive version of the interface gave much poorer results.

Joining forces with the auditory cortex

People often use visualization without thinking about the other potential options for exploring their data. Sonification shows promise as an alternative when visualization cannot do justice to the data being represented; many participants found the sonification a novel and intuitive way to display uncertainty ("It really helped me understand the uncertainty element of the data.") Still, no one can pretend that sonification has anything like the maturity of statistical visualization, which has continued to improve over the centuries.

Much of the bottleneck is technological: graph paper was invented at the dawn of the 19th century, whereas sonification has only started to become feasible in the age of personal computers. It can be still challenging to sonify data without learning audio synthesis languages such as SuperCollider, though a few tools are emerging (see Box 2).

Skeptics can point to plenty of laughing and coughing coming from the computer speakers of sonification. No data analysis task has yet proven itself to be ideal for sonification. Some attempted applications seem truly bizarre, such as a recent paper that used sound clips of cows mooing and monkeys howling to represent the likelihood of a cell being cancerous.

But we shouldn't be embarrassed by our auditory cortex, or the strange new noises we're hearing from data. We need all the mental resources we can muster for understanding the data and models that explain and control the world. Quantifying uncertainty of climate projects, for instance, only helps us if we can teach people to understand and use them correctly for planning. These rough but promising beginnings are the first steps toward letting our data sing.

Box 2: How to listen to your data

The easiest tool for immediately playing with sonification is the Georgia Tech Sonification Lab's free *Sonification Sandbox* (`sonify.psych.gatech.edu/research/sonification_sandbox`). This provides a graphical user interface for importing a comma-separated values file into the program, and allows exploration of different ways of mapping variables to sound parameters and providing context cues to the listener.

Statisticians who peruse a variety of models and predictions may want a solution that integrates more closely in with the analysis and modeling process. The `playitbyr` project (`playitbyr.org`) is bridging this gap in the R programming language with syntax modeled after the popular `ggplot2` visualization package.[3] Newer versions of *Mathematica* also include functions useful for sound synthesis and sonification (`reference.wolfram.com/mathematica/guide/SoundAndSonification.html`).

Whatever tool you use, the recently published *Sonification Handbook*, available online at `sonification.de/handbook/`, is quite helpful for exploring and diving deeper into the many different possible ways of engaging with your data.

References

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2. G. J. Jenkins, J. M. Murphy, D. S. Sexton, J. A. Lowe, P. Jones, and C. G. Kilsby (2009) *UK Climate Projections: Briefing report.* Exeter, UK. (Available from: `http://ukclimateprojections.defra.gov.uk/content/view/826/500/`.)
3. Ethan Brown (2011) The R programming language as a unified environment for data sonification. *Proceedings of the 2011 International Conference on Auditory Display*, Budapest, Hungary.

Ethan Brown is a statistical consultant in the energy industry, created the R sonification packages `playitbyr` and `csound`, and blogs at `statisfactions.com`.

Nick Bearman is an Associate Research Fellow in GIS at the European Centre for Environment and Human Health (ECEHH); he created this sonification tool for Google Maps as well as other spatial data applications (see `www.nickbearman.me.uk` for details).