LISTAHÁSKÓLI ÍSLANDS
Iceland University of the Arts

The data behind the sound

Technical and aesthetical issues in sonification demonstrated by analysis of case studies

Robin Morabito

Final thesis for a BA-degree
Icelandic Academy of the Arts
Department of Music Composition – New Media
November 2021

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Supervisor: Thor Magnusson

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Abstract

Human listening is incredibly well adapted to recognize patterns within sound, interpreting it by multiple layers of meaning and even distinguishing simultaneously sounding “auditory objects”. This is an ability that is not completely understood, but it proves that human auditory system can process data in a complex, yet flexible way. Different disciplines have come to using the auditory system as a channel to transmit multi-dimensional information by transposing it into sound in a process called Sonification, leading to the formation of a dedicated branch of interdisciplinary research around it as core component of Auditory Displays.

This essay will examine different sonification case studies, analyzing their technical and structural features while bringing evidence of the importance of design aesthetic in auditory displays and reflect on the role of sonification as art form. In order to familiarize the reader with the theories behind sonification, a brief overview over auditory displays will be proposed, introducing perceptive and symbolic issues in auditory interface design and underlining elements of connection with contemporary sonic practices.

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1. Introduction

While the idea of encoding non-auditory information into sound is not entirely new[1] it is only since the foundation of the International Community for Auditory Display (ICAD) in 1992 that sonification, a subset of auditory display (AD), has been described systematically and developed rapidly, incorporating approaches coming from the fields of physics, psychoacoustics, computer science, psychology and many others.[2] Before then, sonification was lacking a formal taxonomy: being such a contemporary interdisciplinary field, it was difficult to conduct research in sonification without "focusing on the tree instead of seeing the forest".

In the past thirty years we have seen that sonification, along other ADs, has evolved and been adopted in a multitude of cases. The fields where it finds most applications, and where its potential is clearly visible, span between assistive technologies, process monitoring, auditory alarms, data navigation. According to the current definitions, while *auditory display* usually refers to the entirety of aspects of a human-machine interaction system (from the sound system to the chosen method to display information), *sonification* is intended as the technique of producing nonverbal sound in response to data.[3] It enables us to experience data by listening,[4] to operate an auditory analysis on pattern, features and variations through an AD, and getting information from the data displayed. Such definitions encompasses methods that have been used for a long time (turning non-acoustic information into music, take Pythagoras as an example), even though some researchers[5] consider mainly three inventions from the 19th century to be emblematic for the development of AD and sonification: the telephone (1876), the phonograph (1877) and radiotelegraphy (1895). These inventions made it possible to transform sound waves into electric signals and vice versa, hence registering and displaying sound. The development of media to display the sound made subsequently possible the idea of encoding all forms of data into it, which led to the current research in sonification.

Today auditory interfaces are used for alarms, to deliver notifications and signal changes in the environment, to provide acoustic feedback to visually impaired people and to represent multi-

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1 Andrea Polli, "Atmospherics/Weather Works: A Spatialized Meteorological Data Sonification Project," Leonardo 38, no. 1(2005): 32.

2 Thomas Hermann et al., "Introduction," in *The Sonification Handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 1-2.

3 Bruce N. Walker and Michael A. Nees, "Theory of Sonification," in *The sonification handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 9-10.

4 Thomas Hermann, "Wave Space Sonification," in *Proceedings of the 2018 International Conference on Auditory Display* (Hougton, USA, June 10-15, 2018).

5 Florian Dombois and Gerhard Eckel, "Audification," in *The Sonification Handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 303-304.

dimensional data variating through space and time. Sonification is useful when needing to represent scientific datasets in a parallel way to visualization, but also as an inexhaustible source of inspiration for creation of art; section 2 will discuss pros and cons of sonification in comparison to other display methods and will acclimate the reader to the variety of uses of sonification and its importance as intermediate between sonic arts and data monitoring methods. In all cases, often sonifying data becomes an optimization problem with aesthetical implications – choosing which is the best way to portrait a dataset sonically. This task brings up questions relative to the ways information is encoded, perceived and decoded from the listener. Section 3 and 4 will examine relevant perceptive, psychoacoustic and symbolic properties of sound and how they are taken into consideration in a sonification design. There are several sonification techniques adopted for different problems, and to clarify these differences the sections 5 will introduce the field of auditory display with attention to characteristics and requirements of sonification in section 6. Finally, section 7 will examine examples in sonic arts, focusing on analogies and differences between them to motivate their importance of sonification as creative discipline, beside data analysis tool.

2. Why sonification?

The works analyzed as case studies in this essay all involve sonification techniques. They are different projects whose only commonality is having adopted some kind of data-to-sound translation in their design. The reasons for using sonification might be different: when it comes to interactive interfaces design, for instance, relying only on a visual representation could be limited as devices around us are increasingly ICT (information communication technology) based.[6] The presence of an auditory display makes interfaces more user-friendly or enables the recognition of multi-dimensional patterns in the environment, like the audio-haptic ball discussed in section 7.2. When it comes to data representation, aural and visual have both shown to be practical when wanting to display data sets and gather insights about them.

Sonification and visualization both have their pros and cons, but when it comes to certain tasks, an auditory display might be preferable for an efficient analysis or problem solving. Firstly, sounds can be useful in circumstances where the need to move the eyes to acquire information or following the display is risky, such as driving an emergency vehicle or piloting a plane. Moreover, most of the times it could be counterproductive or non-feasible to look at or see a display, maybe

[6] Daniel Hug, "Towards a hermeneutics and typology of sound for interactive commodities," in *Proceedings of the CHI 2008 Workshop on Sonic Interaction Design* (Firenze, Italy, 2008)

because occupied in another task, because of a visual impairment between the display and the perceiver, or because of information overload.[7]

Both aural and visual perception require context cues in order for the perceiver to keep the interpretation of the data “in phase”: this can be for instance tick marks on a Cartesian plane for visual representations, or periodic clicks in an aural representation,[8] to maintain a perception respectively of the space scale and time scale. However, unlike visual perception, there is no requirement in aural perception for a specific user orientation. This means that visual displays usually require physical and visual disposition in order to be perceived and interacted with, while we can keep an auditory display “in the background” and still being capable of discerning anomalies and regularities within an audible continuum.

However, designing an auditory display using sonification methods can be tricky and have limitations on its own. In particular, intelligibility and reproducibility conditions of a sonification (treated in more detail in section 6) might be negatively affected by a number of factors including: difficulty in performing point comparison tasks with auditory material compared to visual material; subjective response to variations in sound parameters (see next section), or to different sound aesthetics; lack of clear context cues; individual differences in perceiving and analyzing auditory material. Most of these points are currently object of research in order to clarify up to what point sonifications can be feasible and in which contexts. Ultimately, sonification limits are largely perceptive and symbolic questions to be answered: the next session examines psychoacoustic properties of sound and how relevant they are for sonification.

3. Perception and meaning

When it comes to our evolutionary biology, two features of sound are relevant: identity and source location, which are respectively the spectral characteristics and the relative position of the sound source.[9] Aural perception allows us to discern between several simultaneously sounding *auditory objects* within a scene, just like how we can discern individual instruments playing in a track.[10] This multichannel input property becomes particularly useful when wanting to display data coming from

[7] Stephen Barrass and Gregory Kramer, “Using Sonification,” Multimedia Systems 7, (1999): 23-24.
[8] Bruce N. Walker and Michael A. Nees, “Theory of Sonification,” in *The sonification handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 25-26.
[9] Simon Carlile, “Psychoacoustics,” in The Sonification Handbook, 41-42.
[10] John G. Neuhoff, “Perception, Cognition and Action in Auditory Displays,” in *The Sonification Handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 75.

different simultaneous sources, or different data attributes from the same dataset: because sounds can convey a significantly larger amount of information, sonification essentially increases the bandwidth of a human/computer interface.[11] Aural perception is based on a range of acoustic cues to the eardrums encoding the surrounding multisource, complex auditory environment into multichannel sound information; essentially, data is collected from the environment and organized into auditory information. This process relies on how information is encoded in the auditory nerve, and how it is recombined in the brain to discern identity and location of different auditory objects in the same auditory scene.[12]

One of the implications of this in auditory display is that sonification designers can present parameters of a multidimensional data set in reserved auditory channels, each one linked to an auditory dimension (a parameter of the sound source). The auditory dimensions most commonly used in auditory display are *pitch*, *loudness*, *timbre* and *duration*.

• **Pitch** is a subjective psychoacustical attribute of sound, corresponding to the perceived tone of a source. In datasets that span continuously with large changes, musical scales provide a valid pre-existing cognitive backdoor to present quantitative information. There are, however, a lot of individual differences to keep into account, given that pitch detection ability is hard to correlate and detect.[13] Even though, it was proven that musical intervals are capable of influencing pitch perception having greater meaning.[14]

Where referring to pitch changes, the direction of such changes (**polarity**) is a relevant attribute to consider:[15] changes with positive or negative polarity (respectively increasing and decreasing pitch) can be associated with different meanings by different individuals. Relationship between polarities and perception of them is still object of studies.

• **Loudness** is the amplitude of a signal: it is used more carefully in sonification, as the resolution in discriminating sounds with different amplitudes is less precise than the resolution in discerning frequencies, along with loudness memory being less developed than pitch memory. Loudness is more susceptible to environmental interferences and has less pre-

[11] Núria Bonet Filella, "Data Sonification in Creative Practice," PhD diss., (University of Plymouth, 2019): 3.
[12] Permagnus Lindborg, "Interactive Sonification of Weather Data for *The Locust Wrath*, a Multimedia Dance Performance," Leonardo 51, no. 5(2018): 467.
[13] Joy E. Ollen, "A Criterion-Related Validity Test of Selected Indicators of Musical Sophistication Using Expert Ratings," PhD diss., (Ohio State University, 2006).
[14] Stanley S. Stevens and Hallowell Davis, *Hearing: Its Psychology and Physiology* (London: John Wiley Amp Sons Inc., 1938), 83-88.
[15] Nicolas Férey et al., "Multisensory VR interaction for protein-docking in the CoRSAIRe project," *Virtual Reality* 13, no.4(2009): 23.

existing cognitive structures to adopt.[16] However, it can be efficiently used in music, where the presence of a reduced number of states (piano, mezzo-forte, fortissimo etc.) makes possible to map loudness in a more perceptually relevant way.

• **Timbre** is quite hard to define, but American National Standards Institute provides a negative definition of it as "the attribute of auditory sensation in terms of which a listener can judge that two sounds, similarly presented and having the same loudness and pitch, are different".[17] It has been used extensively in sonification, both as a continuous and discrete dimension.

• **Duration** has been proven to be crucial: if an auditory display or stimulus exceeds about 12 seconds, it is likely that the initial memory of the event will be progressively degraded – in a sonification context, this means for instance reducing the fitness of a model in which the perceiver has difficulties to make connections and built stream memory.[18]

Hug[19] extends the phenomenological properties of sound adding:

• **Pervasiveness,** the omnipresence of sound that makes impossible to "listen away" from a source in our auditory range.

• **Temporality**, relevant for the way sound events are intrinsically dynamic processes; in a sonification, the impossibility of complete stasis can make analysis tasks more difficult.

• **Spatiality**, directly related to sound multidimensionality: auditory perception over a scene is holistic and omnidirectional and environmental elements are inevitably imprinted in it.

• **Emotionality** is probably more evidently manipulated in movie soundtracks, where some researchers claim the existence of a proper semiotics of film music.[20] Furthermore, foley art in film proves that being able to identify the actual sound sources is not as necessary as identifying abstract qualities, peculiar to each sound event, to building meaning out of them.[21]

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[16] John H. Flowers, "Thirteen years of reflection on auditory graphing: Promises, pitfalls, and potential new directions," *Proceedings of the 2018 International Conference on Auditory Display* (Limerick, Ireland, July 6-9, 2005): 407.

[17] American National Standards Institute. "American National Psychoacoustical Terminology." New York: American National Standards Association, 1973.

[18] Terri L. Bonebright and John H. Flowers, "Evaluation of Auditory Display," in *The Sonification Handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 134.

[19] Hug, "Towards a hermeneutics and typology of sound for interactive commodities," 12.

[20] Alessandro Ansani et al., "How Soundtracks Shape What We See: Analyzing the Influence of Music on Visual Scenes Through Self-Assessment, Eye Tracking, and Pupillometry," Frontiers in Psychology 11, no. 2242 (2020): 2.

[21] Hug, "Towards a hermeneutics and typology of sound for interactive commodities," 13.

Lastly, constant interaction between auditory dimensions has to be taken into account as well: not only auditory dimensions can affect themselves, but also each other - meaning for instance that duration can affect perception of timber, loudness can alter the perception of pitch, emotionality can influence spatiality, etc.; hence *redundancy* can sometimes be used to remark changes in dimensions that would otherwise remain unnoticed. Each sonification purpose requires adopting different associations between data parameters and auditory dimensions involved, as long as some level of intelligibility is maintained (see section 5).

4. Sonification aesthetics

It has been mentioned that a sonification is often a design problem, where we need to compromise the highest data readability possible with aesthetically meaningful sound events. Barras and Vickers[22] argue how it is diverting to think of sonification aesthetic as a framework for expressing

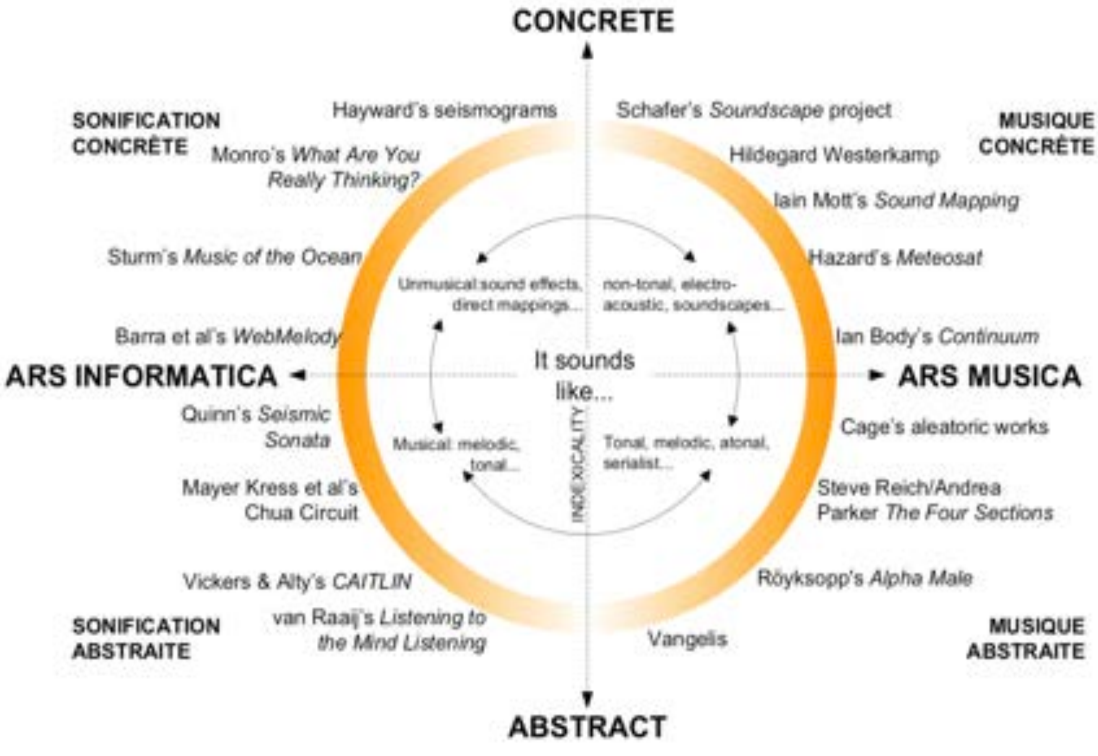

Fig. 1: The Ars Musica – Ars Informatica Aesthetic Perspective Space (from Vickers and Hogg, 2006)

tastes (*analytic aesthetic*), while it is rather useful to think of it as the mean for an effective, sense-making and understandable design (*pragmatic aesthetic*). While this principle would virtually work

[22] Stephen Barras and Paul Vickers, "Sonification Design and Aesthetics," in *The Sonification Handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 159.

as a self-sustaining statement in a data analysis contexts, it appears too reductive when applied to sonic arts; moreover, adopting a strictly pragmatic aesthetic doesn't actually improve sonification readability and intelligibility (see section 5), since little to no actual scientific discoveries have been made by analyzing sonifications alone. Attempts to fix this apparent separation between sonic arts (sensory stimulation) and auditory display (sensuous perception of data patterns) have been made for example by Vickers and Hogg (fig. 1), whom have proposed an aesthetic perspective space associating sonification with their analogues in the musical vocabulary; even then, this representation can't keep into account all the music aesthetics, let alone individual ones. Kramer (1994)[23] and Vickers (2004)[24] have both insisted to include music composers in the sonification design process, idea that should be taken very seriously as it mirrors what is the very core of sonification - its interdisciplinarity. A cross-dialogue between sonic arts and auditory display can help build an aesthetic of sonification and find solutions to common design problems. The next section introduces practical applications of AD and introduces some of the most prominent sonification techniques.

5. Auditory display and sonification

For the purpose of this essay, it is sufficient to introduce auditory display as application of non-speech sounds in human-computer interfaces, to convey meaningful information.[25] This definition includes a lot of algorithms which are essentially sonification techniques and processes; Hermann provided an accurate taxonomy of AD and sonification,[26] them according to their main function and applications. Section 1 has introduced the fields where sonification finds most uses: in some cases, for instance with auditory alarms, sonification usually consists in a single sound event produced after a monitoring system detects crossing an arbitrary threshold; in some others, for instance when monitoring stocks fluctuations or weather data, the need to display multidimensional, continuous data streams calls for further methodologies to be used.

[23] Gregory Kramer, "An introduction to auditory display," in *Auditory Display,* vol. XVIII of *Santa Fe Institute, Studies in the Sciences of Complexity Proceedings* (Reading: Addison-Wesley, 1994), 12-13.

[24] Paul Vickers, "External auditory representation of programs: Past, present, and future – an aesthetic perspective," in *ICAD 2004 – The Tenth Meeting of the International Conference on Auditory Display*, ed. Stephen Barrass and Paul Vickers, (Sydney, 2004): 6.

[25] Kramer, "An introduction to auditory display," 2.

[26] Thomas Hermann, "Taxonomy and Definitions for Sonification and Auditory Display," *Proceedings of the 2008 International Conference on Auditory Display* (Paris, France, June 24-27, 2008).

Earcons and *auditory icons* are more fit for single-event based sonifications. **Earcons** are short, abstract non-speech sounds associated with objects/events in a HCI (human computer interface). User must learn their meaning before being able to understand them properly, but on the other hand they don't require an existing relationship between sound and meaning (abstract sounds can signify actions related to the specific environment of the interface). They can also be grouped according to timbre, pitch and other parameters, as well as organized in families.[27] The error sound in a computer is an example of earcon – a short, abstract non-speech sound associated with failure to complete a task. Such gesture has no real sound equivalent to be associated with, so an earcon is the best solution for this representation problem. But deleting a document, for instance, is an action that could be better represented through its existing sound-meaning relationship (e.g. crumbling paper in OSX), or **auditory icon** – short sounds that have a direct association with objects/events.

However, while earcons and auditory icons are best suit to represent single events, both of them are usually inadequate to portray large data sets, for which other types of sonification are more adapt. **Audification** is definitely one of the first sonification techniques to be used historically: it consists into a direct translation of a data waveform into sound – basically a continuous, non-digital interpretation of data.[28] The Geiger counter (1908) is an example of an auditory display of radiation level, using audification as sonification method. Datasets might need to be scaled to fall within the audible range (when audifying with pitch) and in an intelligible temporal resolution; moreover, the type of datasets considered affects the result of the process, so that the process often involves trying different associations data-sound to actually find structurally relevant patterns.[29] Audification is often used in a "data exploration" phase of the sonification process, that can involve later techniques more well suited for displaying multivariate data: for example, **Parameter Mapping Sonification (PMS)** is implemented where contextual information is associated to auditory parameters, to display data.[30] Categorization of data is relevant for this technique, as it allows to identify channels (or dimensions) and if the data are continuous or discrete; PMS is especially used to display multidimensional data, which our listening system is predisposed to (as reported in the previous part of this essay), thus allowing register, loudness, decay time, stereo localization, duration and silence control implementations.[31] This method can be used to probe data to locate a target sound that approximates

[27] David McGookin and Stephen Brewster, "Earcons," in *The Sonification Handbook,* ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 340-343.
[28] Dombois and Eckel, "Audification," in *The Sonification Handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 302.
[29] Dombois and Eckel, "Audification," In *The Sonification Handbook*, 317-320.
[30] Alice Eldridge, "Issues in Auditory Display," Artificial Life 12, no. 2(2006): 265.
[31] Florian Grond and Jonathan Berger, "Parameter Mapping Sonification," in *The Sonification* Handbook, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 380-381.

a known source sound; a good way to display complex data from EEG, turbolences, metereological data, hyperspectral imaging, geophysical data, hierarchical networks.[32] Scaling is always a concern in PMS and pretty much in every sonification technique; context, in this case, is just as relevant (the use of tick marks on Cartesian axes in the example in the introduction). PMS for musical applications (sometimes referred to as **Musification**) is quite common and can involve sonifications of atemporal datasets (such as DNA or protein sequences, like the *Viral Counterpoint* in section 7.2)) or time-variable ones (weather, solar activity, brain activity –like Lucier's *Music for Solo Performer* dated 1965 - etc.).

When dealing with atemporal data sets, time dimension can be successfully substituted by an interactive dimension. On this direction, an interesting implementation was provided by Thomas Hermann, introducing **Model Based Sonification (MBS)**[33] where a particular focus is put into user interaction. MBS requires a 1) model setup, or how data defines the configuration of a dynamic system; 2) model dynamics, or a mapping of how the system can change in time; 3) model excitation, defining the degree in which the user can interact with the system; 4) initial state, which requires a comprehension of the equilibrium points in the model dynamic to set a "zero" state accordingly; 5) model link-variables, a way to compress variables together and spare computer power; 6) listener characteristics, addressing the location, orientation or distance of the link-variables and the user/listener.[34] MBS is rarely used for time-variating parameters, and models have evolved to deal with specific analysis task; however, it remain mostly efficient in exploration contexts, to get structure-specific information about the data. The *Audio Haptic Ball* is a good example of an auditory display using MBS framework as sonification method, and a specifically developed model (Data Solid Sonification Model) to let a user interact with sound structures through a haptic controller.[35] This form of user interaction has deepened the possibilities of MBS both as data analysis tool and as a real time audio controller; section 7.2 will treat this topic in detail. Notably it is very common to use hybrid approaches to sonification, as can be seen in sections 7.1.

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[32] Florian Grond and Jonathan Berger, "Parameter Mapping Sonification," in *The Sonification Handbook*, ed. by Thomas Hermann, Andy Hunt and John G. Neuhoff, 363-397. Berlin: Logo Publishing House, 2011.

[33] Thomas Hermann et al., "Sonification for Sonic Interaction Design," in *Proceedings of the CHI 2008 Workshop on Sonic Interaction Design* (Firenze, Italy, 2008), 36.

[34] Thomas Hermann, "Model Based Sonification,", in *The Sonification Handbook*, ed. Thomas Hermann, Andy Hunt and John G. Neuhoff (Berlin: Logo Publishing House, 2011), 403-408.

[35] Thomas Hermann, Jan Krause, and Helge Ritter. "Real-Time Control of Sonification Models with a Haptic Interface." *Proceedings of the 2002 International Conference on Auditory Display* (Kyoto, Japan, July 2-5, 2002): 1.

6. Requirements and applications

Although music and other methods can already intersect much of what described above, a technique can be called "sonification" only under certain conditions, including: *reproducibility*, meaning that given the same conditions (data and interactions) the resulting sound can be structurally the same;[36] *intelligibility*, or that "objective" properties or relations in the original data are reflected systematically in the output sound;[37] but also *readability* (especially if using computer programming as working frame) and some level of *crafting* to produce sound environments resonating with the broader acoustic experience.[38] Even though this aspect might seem misleading in data analysis contexts, it has relevance in sonification design as it comes from aesthetic concerns that are more peculiar of sound arts than auditory display (see previous section).

Scaletti[39] proposes a definition of sonification as "a mapping of *numerically represented relations* in some domain under study to relations in an acoustic domain for the purpose of interpreting, understanding, or communicating relations in the domain under study". The attention put on *numerically represented relations* in place of *information* underlines the presence of a context, a framework where such relations can become visible in analysis.[40] In light of this characteristic, one could argue that music and sonic arts offer the perfect environment to apply sonification techniques to – even then, these ideas have struggled to find support in the auditory display community, and attracted some criticism. Some researchers such as Wolfe point out that the ears are "unreliable witnesses" and that the experience of sound is demonstrably subjective.[41] This essay tries to demonstrate through the examples proposed that this feature of sound is particularly suited to welcome sonification processes into sound expression, even though the information displayed might just be *experienced* and not *understood*. Musification, for instance, sublimates this tendency into two usual approaches to it: one that sees it as sonification with musical constraints, the other considering it as sonification for artistic purposes. In general, musification is a type of sonification following musical rules, while also existing as a piece of music,[42] definition that resonates with the examples in Section 7.1.

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[36] Walker and Nees, "Theory of Sonification," in *The Sonification Handbook*, 12.

[37] Shawn Graham, "The Sound of Data (a gentle introduction to sonification for historians)," *Programming Historian* 5 (2016).

[38] Scot Gresham-Lancaster and Pete Sinclair, "Sonification and Acoustic Environment," *Leonardo Music Journal* 22 (2012): 69.

[39] Carla Scaletti, "Sound Synthesis Algorithms for Auditory Data Representations," In *Auditory Display,* vol. XVIII of *Santa Fe Institute, Studies in the Sciences of Complexity Proceedings*, 223-225. Reading: Addison-Wesley, 1994.

[40] Bonet Filella, "Data Sonification in Creative Practice," 3.

[41] Kristina Wolfe, "Sonification and the Mysticism of Negation," *Organised Sound* 19, (2014): 303-304.

[42] Bonet Filella, "Data Sonification in Creative Practice," iv.

7. Case studies

To test the theory and the implementations presented so far, a simple methodology of analysis of objective parameters is now proposed. For each work/body of works involved, several structural, technical and aesthetical features will be considered according to those introduced by Barras and Hotakeinen in 1994:

- *dataset*, alias the initial raw material (data) used;
- *criteria*, requirements/rules/associations followed for the piece itself;
- *data handling*, or which system has been used to sort the data;
- *data analysis*, or criteria used for the sonification (associations data-parameter)
- *mapping*, sonification technique adopted;
- *sound design*, details about the sound synthesis used;
- *composition/auditory display*, an overall look at the work(s) examined both as sound pieces and auditory display;
- personal *observations* about the piece(s).

These parameters were proposed with the project *Listening to the Mind Listening*, which was realized in 2004 and produced a body of 27 different multichannel sonification by 38 composers, from the same dataset (a recording of Evian Gordon's electrical brain activity while listening to David Page's *Dry Mud*[43]); The "Concert Call for sonification" was performed at the Sydney Opera House as conclusion in the same year.

This work is considered relevant in light of its clear methodology and for the huge contribution it brought to sonification research: the results showed how, regardless the use of different data mappings, sonification techniques and sound design systems, all the participants provided similar temporally placed audio cues, letting intend that all of them could extrapolate peaks amongst values.[44] Moreover, while scales of *aesthetics, mapping, accessibility* and *overall impression* were asked to be defined according to each pitch, it was found that each scale predicted any other.

The next two sections will introduce respectively two examples of hybrid musifications and an example of user-interactive MBS, analyzed in a similar manner as enounced above.

[43] Stephen Barrass, Mitchell Whitelaw and Freya Bailes, "Listening to the Mind Listening: An Analysis of Sonification Reviews, Designs and Correspondences," *Leonardo* 16, (2006): 13.
[44] Barrass et al., "Listening to the Mind Listening", 16-17.

7.1 *Viral Counterpoint* and *Brexification*: examples of hybrid sonification techniques

The two sonifications here displayed seem perfect examples of balance between design and functionality: one is a methodical PMS for scientific purposes, adopting an approach defined as "materiomusical" by its creators;[45] the other is an example of carefully crafted sonification involving audification and PMS with further manipulations on sound driven by aesthetical and symbolic choices.[46]

Viral Counterpoint for the Coronavirus Spike Protein (2019-nCoV) by Markus J. Buehler consists in a hour and fifty minutes long piece of music, released in 2020 alongside a research paper. The project used a nanomechanical sonification method allowing to express protein structures from 2019-nCov virus spike protein in audible space.[47] Proteins are composed by chains of aminoacids and organized in different levels of folding: primary-order (the linear aminoacidic sequence); secondary-order structure (regular, repeated patterns of local folding in the protein backbone, most commonly *alpha helix* or *beta sheets*, respectively a helicoidally coiled chain or a flat sheet); tertiary-structures (overall compact folding of the polypeptide chain in a 3D space); quaternary-structures (emerging from combinations of tertiary structures in proteins composed by more than 1 polypeptide chain). The spike protein in this case is composed by 3 polypeptides in its quaternary structure.

- **dataset**: amino acid sequences, secondary structures, and environmental interaction of 2019-nCov spike protein (PDB reference ID 6vsb [48])
- **criteria**: mapping each of the 20 aminoacids to a unique musical tone; primary sequence defines the sequence of notes played, augmented by the other components; secondary structures (alpha helix and beta sheets) affect duration and volume; tertiary structures are codified as direct audio signal, traducing vibrational motion frequencies into sound (materiomusic).
- **data handling**: data coming from audification of the molecules vibrational states, as well as those obtained from analysis and scaling of primary and secondary sequences, are played together to generate a multi-dimensional auditory image of the protein sequence and peptides interrelations. The sequential aminoacids have been transposed in a dorian mode framework.
- **data analysis:** amino acids TYR, ASN, LEU, MET, GLU, PRO, TRP, ARG, GLN, HIS,

[45] Sebastian L. Franjou, Mario Milazzo, Chi-Hua Yu, and Markus J. Buehler, "Sounds interesting: can sonification help us design new proteins?," *Expert Review of Proteomics*, 16 (2019): 1-3.
[46] Olaf Livieri, "Brexification," (BA thesis, University of West London / London College of Music, 2017), 7-9
[47] Markus J. Buehler, "Nanomechanical sonification of the 2019-nCoV coronavirus spike protein through a materiomusical approach," arXiv (Popular Physics), March 30, 2020, https://arxiv.org/abs/2003.14258.
[48] This 4 digits ID allows to retrieve the 3d model of the molecule via Protein Data Bank: https://www.rcsb.org/structure/6VSB.

PHE, SER, LYS, VAL, ASP, THR, ILE, CYS, ALA, GLY disposed in ascending order and pitch; relations between amino acids inside the multilevel protein structures are respected and portrayed in music.

- **mapping**: materiomusic, of Buehler invention, is the approach used to map source data into auditory information according to the natural occurring structural vibrations of large biomolecules such as proteins. In light of what has been displayed so far, we can picture materiomusical sonifications as PMS requiring vibrational models of the molecule sonified.
- **sound design:** formatted data were rendered through Max/MSP and Ableton Live
- **composition/auditory display:** this auditory display was meant to be considered for its scientific, rather than strictly artistic, value and purpose. When it comes to proteins 3d structures, a combination of sonification and deep learning could be an incredible powerful tool while synthesizing analogues or predicting binding sites or reactive centers on a protein tertiary structures. Even though, this piece shows also a quite robust mapping model that can make quite evident the impact of singular events (e.g. a single aminoacid in the primary sequence, or a single alpha helix on the secondary) on the overall system. On the other hand, this sonification requires some previous knowledge and biochemical background to be understood in context.
- **observations:** Buehler is not new to this kind of experiments and has refined his materiomusical model through the years with a very interdisciplinary approach to sonification: in 2021, for instance, he was involved in a project aimed to realize new material designs by sonifying flames and using deep learning to recombine the data obtained into new data sets.[49] Even without undergoing a formal music career, his research has given us some really interesting pieces of music and shows quite concisely the potentiality of sonification for displaying complex data structures such as protein multidimensional structures.

Interesting musical results have also been obtained by Ollie Magma, with his 2017 body of work *Brexification: A Sonification of Brexit*, also a 5-tracks album.[50] Like the Viral Counterpoint, Brexification shows that a good sound design isn't only helpful for a sonification, but also necessary: with a combination of music programming and in-DAW editing, the work ambitiously portraits the Brexit through sonification of data from 5 crucial steps in the process.[51]

[49] Mario Milazzo and Markus J. Buehler, "Designing and fabricating materials from fire using sonification and deep learning," *iScience* 24, no. 8 (2021).
[50] Ollie Magma, "Brexification: A Sonification of Brexit," 2017, Anti System Records, digital release.
[51] Livieri, "Brexification", 2017.

- **dataset**: several used, including: letters and words' length from Art. 50 of the Lisbon Treaty document; pound-to-euro peak values and monthly crime data from Jan 2016 to Aug 2017.
- **criteria**: all the compositions had to contain data obtained from material relative to the Brexit
- **data handling**: the datasets have been mostly handled as MIDI parameters first via Jython for Music, then Ableton Live. determining quantitative sound properties (pitch and duration) and leaving to Ollie Magma most freedom of choice over qualitative properties and metastructures.
- **data analysis:** 26 letters-note association (mechanism based on a Guido D'Arezzo's algorithm from ca. 1000); durations proportional to words' length.
- **mapping**: mostly PMS, where historical symbols are used somehow as a mappable parameter (dimension).
- **sound design:** entirely in Ableton Live.
- **composition/auditory display:** this work is conceived as a 5 chapters music composition; compared to the previous example, it is musically much more complex and varying while still adhering strictly to the chosen criteria and data mappings; with knowledge about the album themes and leitmotivs, readability increases sensitively.
- **observations:** Ollie Magma's work proves that when sonifying data for musical purposes it is actually an aesthetically rewarding choice to be as wide as possible in the sound design stage, and displays how from similar datasets it's possible to obtain different designs (property that was demonstrated by *Listening to the Mind Listening*); moreover, Brexification does actually succeed into communicating trends and data peaks to the listener, success that is less determined by the choice of data sets and more by the data mapping methods, together with a solid narrative from where to access comprehensible symbols.

7.2 *Audio-haptic ball*: interactive sonification of atemporal datasets

While none of the two previous works proposed was executed in real time, this context offers a lot of opportunities in sonification. Of course working with real time data requires a robust data handling and instrument mapping system, for which the audio-haptic ball realized by Hermann, Krause and Ritter in 2002[52] is a perfect example.

[52] Thomas Hermann, Jan Krause, and Helge Ritter. "Real-Time Control of Sonification Models with a Haptic Interface.", 1-5.

This device consisted in a physical interface for controlling sonification models (fig. 2), hence providing a better case study for interaction sounds, characterized by the presence of an acoustic feedback between the model, and the actions that the user can perform on it. This project is inherently different from the other two proposed above, as its real time component is treated as an additional dimension in the model.

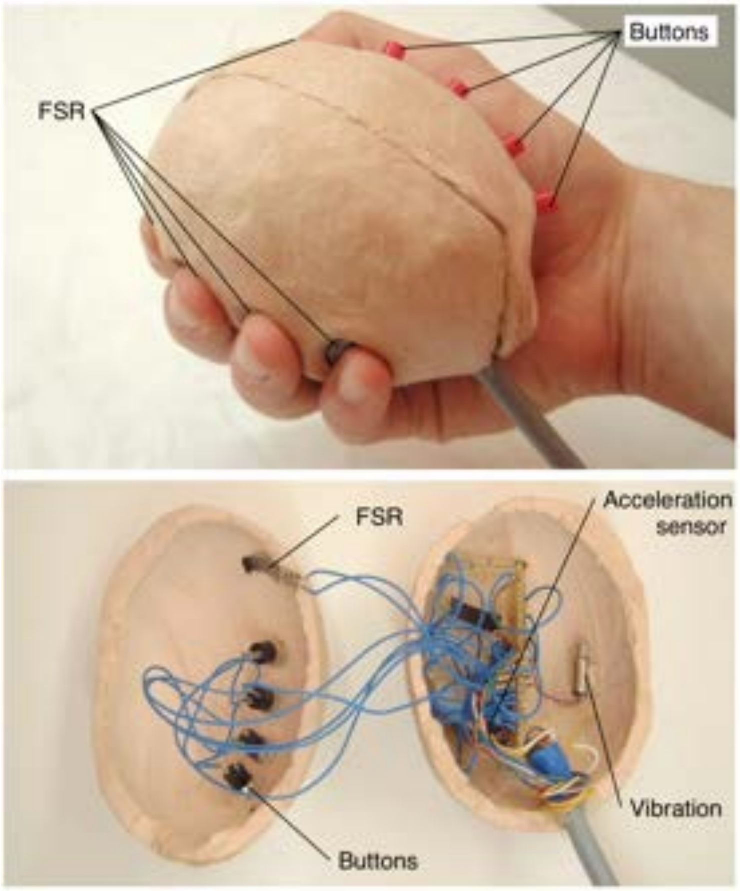

Fig. 2 Prototype of the audio-haptic ball

- **dataset:** a growing neural gas (GNG) algorithm is used to obtain a reduced representation for a synthetic datasets for a binary classification problem.
- **criteria:** the audio-haptic ball has to have an ergonomic size; sound generation must be real time with a latency of max 5ms; the model can be excited by shaking, moving, touching or rotating the ball.
- **data handling:** the neural gas is characterized by weight vectors for each neuron, and a list of undirected connections (or edges) between the neurons; a learning algorithm adapts neuron weights and edges as the user interacts with the audio-haptic ball. In a resting state, with no interaction, all objects will remain at their center coordinates; however, when a user interacts with the ball, the distance between neurons and their edges will vary, causing perceivable changes in the sound.
- **data analysis:** 3d acceleration measurement, 2d inclination measurement, surface force measurement.
- **mapping:** Data-Solid Sonification Model, introduced together with the audio-haptic ball as a way of rendering acoustic representations for high-dimensional data; it is found in the framework of MBS, where exploration of the dataset is performed by interacting with the model.[53]

[53] Hermann et al., "Sonification for Sonic Interaction Design," 37.

- **sound design:** at the time, a dedicated C++ library (Real Time Audio Toolkit for Sonification) was being developed.
- **composition/auditory display:** this project revolved around the realization of an audio-haptic ball device, consisting of an ergonomic ball-shaped case integrating various sensors, on the outside and the inside – six *force sensors* (FSR) for fingers mounted in depressions on the surface, *acceleration sensors* (two 2D orthogonal accelerometers on a chip), four *piezo sensors* in a plane pad, four *programmable buttons*, a *vibrational actuator* to provide vibration feedback.

- **observations:** this piece introduced the notion that virtual objects or large datasets can (and should) be approached as virtual models to be navigated: it also shows that interactivity of a model is a powerful way to extend the scope of sonification horizontally, in the sonic arts field and in data analysis. In 2008, Özcan and Çamcı got to produce an augmented reality music composition (Propius) based on the sonification of animal behavior,[54] exploring ecological model and algorithmic art; in this piece, the composer/listener doesn't interact directly with the sound produced, but rather on the artificial organisms generating them. Through the sonification of their virtual characteristics and behaviors, the listener gets to interact with the surrounding virtual auditory reality in a mutual feedback mechanism. The complexity of this work (which is an augmented MBS) shows pretty clearly the width that sonification has reached today, wrapping up all the notions introduced so far while leaving the reader to the expanding world of sonification.

[54] Zeynep Özcan and Anıl Çamcı, "An Augmented Reality Music Composition Based on the Sonification of Animal Behaviour" (AES Conference on Audio for Virtual and Augmented Reality, Redmond, USA, August 20-22, 2018).

8. Conclusion

This essay examined three works adopting sonification techniques as musical systems, addressing the variety of applications made possible by auditory display theories while demonstrating the interdisciplinarity of sonification and its peculiar place between sonic arts and data analysis. At the current state of research, these examples should only picture fundamentals in the development of sonification, while attention should be directed at future developments and experiments.

An introduction over auditory display and sonification was necessary to acclimate the reader with the complexity of the subject; at the same time, it seemed necessary to present this research topic within its larger context and framework, being aware of the increasingly data-based structure of devices and interfaces around us.

Sonification is one of the fields where sonic practices and scientific research find a natural point of contact, and it's fascinating to acknowledge the progress made since the auditory community was brought together mainly by ICAD conferences. In the coming years, it is realistic to expect both data analysis and sonic arts to involve more auditory display, given the extreme flexibility and multi-dimensional resolution of auditory inputs, and definitely find deeper connections between disciplines and artistic practices.

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