POTENTIAL USE OF SONIFICATION FOR SCIENTIFIC DATA REPRESENTATION

G.I. MIHALAŞ*, ***#, MINODORA ANDOR**, ANCA TUDOR***, S. PARALESCU**

*Commission of Medical Informatics and Data Protection, Academy of Medical Sciences, Romania
**Department of Medical Semiotics, "Victor Babeş" University of Medicine and Pharmacy, Timişoara
***Centre for Modelling Biological Systems and Data Analysis,
"Victor Babeş" University of Medicine and Pharmacy, Timişoara, Romania
#e-mail: mihalas@umft.ro

Abstract. This review paper makes a synthetic survey on 'sonification' – a novel procedure to represent data by sounds. The Methods section comprises a short theoretical background of the domain, focusing on the mapping algorithms, associating sound parameters (pitch, duration) to major data parameters (amplitude, sequence time-course). It also refers to various ways to improve the acoustic perception for specific cases – tempolenses, saccadic displays, loudness. The Results section starts with enumeration of most popular sonification software packages, some references of various applications, including also some of our results for sonification of ECG or heart rate during exercise, including a short description of our methodology for estimating the discriminant power by comparing various sonic displays of the same set of data. The comments of the Discussion section can be viewed as suggestions for future work and finding new applications.

Key words: data representation, sonification, auditory display, tempolenses, heart rate, ECG.

INTRODUCTION

An important tool for interpretation of scientific research results is data representation. Quite often it is considered synonym to visualization, as we mostly rely on the visual system as the major informational input to the brain. But, our brain is fed by other sensory systems as well, including the auditory system. Several attempts have been made, indeed, to explore the potential use of sounds as informational carriers and this paper intended to offer a short but systematic overview on the work done in this direction up to now.

Without ignoring the early attempts, we will mainly refer to the period after 1992, when ICAD – International Community for Auditory Display [34] was founded and a certain convergence of views and tacit acceptance of specific

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terminology was noticed. As an equivalent to visualization, the term sonification was introduced and defined as “the use of non-speech audio to transform data into an acoustic signal”. The term auditory display was also introduced and defined as “any technical solution for gathering, processing, and computing necessary to obtain sound in response to data” [36]. With this terminology we can consider sonification as the core element of an auditory display.

For this review paper we have used the excellent survey of the sonification domain until 2011 done by Hermann, Hunt and Neuhoff [11] to which we added our vision, built from our own experience [19].

METHODS

In his *Sonification Report* [13], Kramer identified four issues to be addressed in a theoretical description of sonification:

– taxonomic description of sonification techniques based on psychological principles or display applications;
– description of the type of data and user tasks amenable to sonification;
– a treatment of the mapping of data to acoustic signals, and
– a discussion of the factors limiting the use of sonification.

Walker and Nees (chapt. 2 in [11]) extended a classification of Buxton [6] and described the function of auditory displays in:

– alarms, alerts, and warnings;
– status, process, and monitoring;
– data exploration;
– art, entertainment, sports, and exercise.

They have also considered that, from a practical point of view, a display designer has to start from the user needs for defining his task(s), to identify which data are relevant to the task, to decide upon the type of display and find an appropriate method to process the data.

Regardless the type of display, the central issue in sonification theory is the mapping – to define a relation between the major physical parameters of a sound – frequency (pitch) and/or duration with (major) properties of the data to be represented. There is a large variety of methods proposing more or less conventional relationships. De Campo (chapt. 10 in [11]) tried to classify the methods into: (i) event-based, (ii) model-based and (iii) continuous. For instance, in the event-based methods – the simplest and mostly encountered procedures, usually the amplitude (intensity) of the major variable is translated into the sound frequency, while other properties of the data set can be linked to other properties of the sound sequence – duration or intensity or even raising the complexity of representation by introducing rhythm, harmony, instrumental timbre, multiple tracks, etc.

We will present here our approach [18], which has multiple similarities with the one in [11].

DATA TYPES

The information we can extract is highly dependent on the available data type. There are specific classifications of data in various domains – mathematics, statistics, informatics, engineering or (bio)physics. However, up to now, the approach of data types for sonification was somehow ambiguous.

Our approach starts from the idea underpinning the sonification – to associate sounds to data in a way to make possible the distinction between data or detection of changes. It is like in thermodynamics where we define a system, characterize its state by a set of state parameters and a process as a sequence of states, introducing also specific measures for the process. Thus, we can have:

– state data, which can be classified like the statistical variables (qualitative, numerical – ratio or interval, and ordinal),

– process data, comprising the properties of the time evolution of the system. We can introduce here the taxonomy from signals processing: non-periodical or periodical, slow or fast changing.

As a state is usually characterized by a set of parameters, by sonification we will get a composed sound, but, when only one variable is relevant, we can dismiss the irrelevant (constant) sounds.

This classification is useful for most cases, including all types of signal analysis, even the sonification of images. But the similarity is limited in some cases – like sonification of molecular sequences, where instead of tracing the time evolution of the system, we do rather represent the structure.

FORMALIZATION LEVELS

We will first refer to two major parameters of a sound – frequency (pitch) and duration – and present them here like in [18] and [19].

Frequency

Levels. From a physical point of view, there are two distinct levels, corresponding to the sonic output: continuous or discrete frequency spectrum. However, for the purpose of potential applications we will prefer to define three levels:

– acoustic level – with a continuous frequency spectrum;

– sonic level (S) – with a discrete spectrum, having values belonging to the musical scale;

– musical level (M) – a complex level, with multiple channels, rhythm, and harmony.

Scaling. Since original data can be expressed by numbers in any domain, they are usually normalized (y_i), to fit an interval – the simplest [0;1] interval. A reference frequency (f_0) is also needed to yield results within the audible interval. Some practical values for f_0 would be 440 or 262 Hz (A4 or C4 on musical scale). Since the natural sound scale is exponential, for the acoustic level, the sound will have the frequency, f_i, given by:

$$f_i = f_0 \times 2 \wedge (y_i)\,. \tag{1}$$

For the S level, the f_i values are rounded to one of the values from the musical scale.

Transition

When the original data come from a time series, it is possible to preserve the sound duration equal to the real duration of the corresponding event, or introduce a different temporal scale for the sound display – tempolenses, which will be detailed in the subsequent section.

As most often the data acquisition is done by sampling, the data become discrete. Hence, we have to establish a convention for displaying the transition between two consecutive sounds. There are two major possible transitions:

– continuous transition (also called sublevel A), when for two successive points, at t_i and t_{i+1}, the frequency will vary continuously from f_i to f_{i+1};

– discrete representation, when frequency f_i will be displayed for the interval dt = (t_i, t_{i+1}), followed then by f_{i+1} and so on. Usually, the intervals dt are very short and this sub-level was called “quasi-continuous” (Q).

This split into subdivisions A and Q sublevels was done only for the acoustic level, using for the S level longer durations, in order to be perceived as separate sounds.

The reader can hear a sonified signal by the three levels, A, Q, and S by accessing the Demo section of our site [32].

SOUND DISPLAY

Once the first step of parameter mapping is performed (frequencies and transitions), the second step will refer to the time display.

Tempolenses

For the representation of phenomena in real time (like biological signals – ECG, EEG, etc.), the duration of the displayed sound might be kept equal to the duration of the real event. However, we might have very fast, or very slow processes, which would rather require a time scaling, by either compressing or dilating procedures, also called tempolenses [17]. The main parameter of a tempolense (TL) would be the magnification, defined as the ratio between the sound display duration (t_{repr}) and the corresponding real process duration (t_{real}):

$$m = (t_{\text{repr}}) \big/ (t_{\text{real}}). \tag{2}$$

For $m < 1$, we compress the signal – recommended for exploring slow processes, while for $m > 1$, the TL dilates the signal, good for detecting details of fast processes. We have also analyzed in detail the case of TL's with variable magnification (TL-*v*). Unlike the TL with fix magnification (TL-*f*), for TL-*v*, the magnification is $m < 1$ in certain regions and $m > 1$ in other regions – a version recommended for detailed representation of fast processes, without an overall sacrifice of the total displaying time. For instance, for the ECG sonification, the QRS complex is a fast event and would be better heard if dilated, while the T–P interval does seldom contain relevant events, and can be compressed. A better perception would be achieved if sonification would run in parallel.

Sound artefacts in event-related and monitoring applications

One of the directions which proved to be fertile for sonification applications is the use for monitoring processes and/or detecting 'events' – (sudden) changes of quasi-stationary states. These applications are actually based on two major properties of the auditory system:

– it offers a distributed attention, as opposed to the visual system which offers rather a focused attention;

– it contains mainly phasic receptors (having a fast and efficient adaptation, *i.e.* a decrease of the response at a constant value of stimulus intensity), hence an interrupted sound or a change of intensity would be better perceived than a continuous sound.

Various solutions have been proposed, mainly including two sound artefacts.

- ***Saccadic display***: Instead of a single sound we can introduce a saccade of two or three short sounds as a warning (alarm, alert). Moreover, some patterns can be used for different situations; these patterns can be easily learned (if not too many).
- ***Intensity (loudness)***: The intensity of the sound can also be varied, corresponding to different levels of warning, especially when reaching alert regions of the major parameter (for instance, the heart rate during exercise [3]).

NON-TEMPORAL SEQUENCES

For non-temporal sequences, like the primary structure of nucleic acids or proteins, the final result will tremendously vary depending on the convention used for mapping. Some authors defined arbitrarily a relation between the pitch and the corresponding amino acid [24]. However, a numerical variable associated with each amino acid would give a more natural flavour to the mapping. We have tested three such variables: hydrophobicity index, abundance percentage, and molecular weight [32]. In such cases a relation similar to (1) for frequencies can be used. The correspondence map does not have to follow the ordered musical scale, but it might be also linked by some other properties, like the probabilities to find a certain note in a musical composition. Actually, one can imagine a quite large variety of mapping systems and it is difficult to qualify/score them [25].

RESULTS

The chapter on Results is divided into two main sections – one dedicated to the efforts towards building specific software for data sonification and the other to the applications themselves; a subsection here will comprise our own results.

SONIFICATION SOFWARE

The exotic flavour of such a task – to build specific software which can turn data into sounds (especially into "music") seems, indeed, an irresistible challenge. Thus, several projects started in various parts of the world, yielding finally to a quite consistent set of programs, more or less general or performant. There are in general two major kinds of programs: non-interactive (concert-mode) or user initiated (the listener may control the parameters and the display).

Our list below is far from being complete, comprising some of the most known packages or media:

- xSonify [7];
- Sonification Sandbox [29];
- SoniPy [30];
- SuperCollider [15];
- CSound [27];
- AudiolyzR [23];
- PureData [22];
- Gene-2-music [24];
- AlgoArt [9].

Most of the packages enumerated above are open source and can be easily downloaded or are interactive and the user can just input his data and get the corresponding sound stream.

Our applications have been developed in MATLAB, using, besides the main script, specific functions for the main three levels A, Q, and S defined above. The output was saved as wav files [17, 32].

APPLICATIONS OF SONIFICATION

The palette of sonification applications is very large. They can be classified from different points of view. The classes were defined in [36] upon the major purpose:

- information systems for visually impaired people;
- process monitoring applications;
- human-computer interaction;
- alternative to visual display;
- exploratory data analysis.

A good survey was also presented in [11] by Edwards (chapt. 17: Auditory Display in Assistive Technology), Vickers (chapt. 18: Sonification for Process Monitoring), Guillaume (chapt. 19: Intelligent auditory alarms), Brazil and Fernstroem (chapt. 20: Navigation of Data) and Hoener (chapt. 21: Aiding Movement with Sonification in “Exercise, Play and Sport”).

However, the simplest classification would be on the domain of use; some examples are referred below:

- medical applications: EMG signals [21], cardiac signals analysis (heart rate [5, 16], ECG [19], pulse waves) [32], foetal and maternal heart rates [35], pulse oxymetry in operating rooms, EEG signal processing [12, 26];
- general physics [31],
- theoretical physics [28];
- biophysics [8];
- astrophysics [14];
- geophysics: seismic and volcanic activity [1];
- bioinformatics [24, 25, 32].

The references of the applications enumerated above do contain also links to specific sonic examples.

OUR RESULTS

Our concerns about sonification began about 6 years ago with two distinct periods. The first period had mainly an exploratory character. To remove any constraints imposed by the use of software created by other users, we have built our own programs (in MATLAB 2011b) in a modular way; thus, we could combine various types of mapping, with different transition types and adjustable displaying parameters.

We have used as input data mainly cardiac signals, both from experiments carried out in our university [19], or from Physiobank [10]. We paid a special attention to the estimation of the discriminant power of the auditory system to distinguish various displays of the same input signal and finding the optimal set of parameters for the mapping [2].

The second period was mostly oriented towards user needs, trying to develop an event related program for warnings during exercise [3, 4]. Again, several displaying types have been tested in order to design an optimal warning system. We have also joined the main stream of research in this area by participating in an ICAD conference [18]. Exploratory searches continued by approaching also the sonification of molecular sequences [32].

Some major results will be shortly presented and referred below.

Human heart rate (HR)

HR is one of the simplest signals to record, either from pulse oxymeter devices or from ECG. Actually, it was one of the first attempts to sonify a physiological signal done by Ballora [5], but he tried a mapping to the musical level while we tried to keep closer to the original signal [16, 18, 19]. Our comparative study showed that the sound produced by the acoustic level A (sounds like whistling) is neither attractive nor informative. The same is true also for Q sublevel with very short durations. But, the sublevel Q with larger durations or level S sound better and seem appropriate for detecting deviations from normal (sinusal) rhythm. The reader can listen to our examples on our web page with free access [32]. The sonification parameters are listed for each example.

Mouse pulse wave

The experimental results from the physiopathology departments comprised recordings of mouse pulse waves performed for long durations (2–3 hours); a compressing tempolens of 4 to 10 times was tried for facilitating the visual exploration.

ECG analysis

High expectations were expressed from the sonic exploration of the ECG signal. Interpreting the classical recording is not an easy task, as some modifications are very small. We found the ECG signals the most appropriate to compare various sonification methods [18, 19] and to test the discriminant power of each transposition [2].

Integrated display. By applying several sonification parameter sets for the same signals, including various types of tempolenses [17], and comparing them (Fig. 1) using an integrated display, both visual and sonic, a library of various signals and their sonification was created [32].

Discriminant power. An important issue in our project was to test the discriminant power of various sonic representations, *i.e.* the capacity of listeners to distinguish details and recognize various types when the same signal is represented in different ways. This topic was less explored, the literature being scarce in this direction. Our major results have been presented in detail in a previous publication

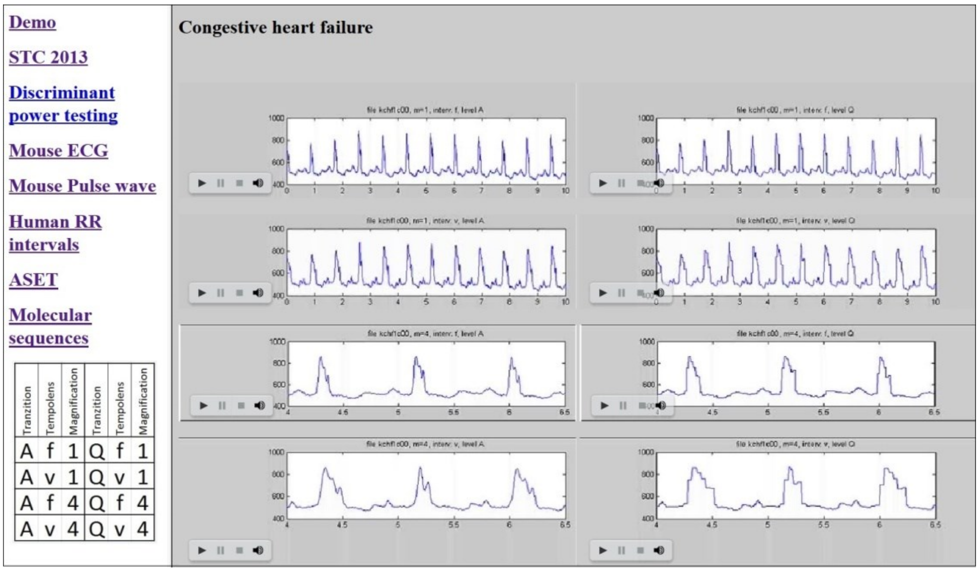
[2] and we will just summarize the major conclusions [19] after a test on two groups of listeners – musicians and non-musicians:

– representation in A mode was less preferred by both groups (it sounds like a whistle); however, it had a higher discriminant power in sleep apnoea, during the obstructive episodes;

– tempolenses with variable magnification did not bring the expected increase in resolution of the QRS complex;

– short durations (less than 0.2 sec) in Q mode sound like A;

– the distinction between Q and S modes was much clearer for the group of musicians, but small differences were noticed for other cases.



Demo
STC 2013
Discriminant power testing
Mouse ECG
Mouse Pulse wave
Human RR intervals
ASET
Molecular sequences

Tranzition	Tempolens	Magnification	Tranzition	Tempolens	Magnification
A	f	1	Q	f	1
A	v	1	Q	v	1
A	f	4	Q	f	4
A	v	4	Q	v	4

Congestive heart failure

Fig. 1. Integrated display for comparison of 8 mappings of an ECG sequence of a patient with congestive heart failure: sound frequency on abscissa, $f_0 = 440$ Hz; mapping parameters legend on bottom left corner: transitions A (continuous) or Q (quasi-continuous), *f* (fix) or *v* (variable) magification tempolens, magnification 1× (10 seconds display) or 4 × (2.5 seconds sequence displayed in 10 seconds real time).

Our studies showed that, even if there were clear distinctions between the sonic display of different signals (normal sinusal rhythm, arrhythmia, and atrial fibrillation), such a simple "adding sound" did not prove to be very attractive to physicians, as their classical procedures did fully satisfy their needs.

Cardiac parameters variation during exercise

One of the applications which have aroused a real interest from users was the warning system to be used during exercise tests, mainly when performed on cardiac patients. The usual professional equipment can trace various parameters during the exercise tests (heart rate, HR, or depression of the ST segment), with warnings when they exceed the preset values (thresholds), but it is mostly visually presented and the patient is passive. Our application adds sounds for various thresholds of HR [3] or ST segment [4]. The threshold warnings for HR have been established using Kevonen relations [33], separating four exercise levels, from quasi-rest up to risk zone. We tested three versions of display and the preferred one had for each exercise zone a specific saccadic sound with a different pitch and increasing loudness (easy to learn and recognize, being useful also for monitoring the training sessions of jogging). The sounds can be also listened to from [32].

Sonification of other types of data

Our experience includes also two other applications (not detailed here):

– cellular kinetics (especially, protein-protein interaction for p53-mdm2 system, a work in progress now) [18];

– molecular sequences (not published, but some examples are posted on our webpage [32].

DISCUSSION

One can easily remark that quite a large amount of work was dedicated to sonification, despite the fact that the major ways of communication and data representation (visualization and speech) cover almost all practical needs. The results and examples presented above, as well as a simple browse on the net data, would give the impression that the field of sonification is already clearly outlined, with well-defined development directions in the future.

However, a more careful analysis would highlight several weaknesses that have limited a more consistent development up to now. Let's list some of these [4]:

– for a while, a weak point was the limited technological support, not fully appropriate for handling sounds;

– several applications (especially, the specific software packages) have not been initiated by future users, but rather to offer a new tool and then expect to find potential users; we think that a successful application should start from a real need, expressed by a future potential user;

– there is still a high degree of conventionality, a lack of a common vision about the core element of sonification – the mapping algorithm, there are no standards yet;

– few studies have been performed about the quality of information perception *via* sonification – discriminant power, sensitivity and specificity, capacity to recognize or memorize patterns, libraries of sounds, etc; little work about the reversibility of transposition – can we reconstitute the initial data from the sonic representation?

– most authors have been mesmerized by the attractiveness of the musical level, perhaps moving us farther from the real signal; we can even ask: do all real data carry harmony?

– sonification, as a new tool, would be accepted and used only if it brings something new, which is not (easily) achieved by other methods; for most practical situation visualization meets expert expectations;

– similar to other systems of symbolic representation, the practical use will require a period of training and learning, especially when complex methods are proposed; this would introduce one more barrier to limit the use of sonification.

The experience, both positive and negative, accumulated during time would let us find the directions to be followed for future successful applications in the bio-medical domain. A simple follow-up of the list above might become a set of recommendations for future work in this domain.

An important, but disputable subject is related to choosing the most appropriate mapping for an optimal sonic representation. Our initial approach – to keep as close as possible to the real physical process, *i.e.* to prefer Q or S display types, does usually yield unstructured sounds, difficult to memorize or recognize. On the other hand, moving towards musical M display type would introduce more conventional mapping, but more structured and with a much higher user acceptance [2, 5, 18, 20]. Further studies are needed for finding the most appropriate balance of “musicality” to be inserted for both preserving the initial information stored by the data and raising the quality of perception up to a practically usable level.

Let’s remark here the potential contribution of biophysicists, not only those working in the field of auditory system biophysics, but also those exploring new ways of complex processes or big data processing and representation [8, 28].

CONCLUSIONS

Sonification is an original method for representation of scientific data, with several potential applications in biomedical research, yet not explored enough. The quasi-conventional sonification algorithms, the lack of well largely accepted procedures or standards have unwittingly limited its application, generating a (still) low user acceptance.

Our exploratory studies presented in this paper allowed us to bring some original contributions to the sonification domain, both in the theoretical background and in the applicative area. Thus, in the Methods chapter, referring to sonification types, we have refined the classification by adding the transition type as a criterion. We have also coined the term tempolens for the time rescaling and introduced the tempolenses with variable magnification. Another interesting area was the development of an appropriate methodology for the assessment of discriminant power of sonic representations. Likewise, on the applicative side of our work, the procedure for finding the set of parameters for the optimal perception of sonic representation heart rate evolution during exercise can be further extended for all kind of monitoring or warning systems.

Finally, the Discussion section, based on the present data and the previous work of the authors, tried to critically analyze the present state of the domain and anticipate promising future directions of work.

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