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Adding Sound to Medical Data

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Abstract. Medical data can be represented in various forms. The most common is visualization, but recent work started to also add sonic representation – sonification. In this study we start with a theoretical background, then focus on medical applications. The discussion synthesizes the authors view about the present state of the domain and tries to foresee future potential developments in medicine. In conclusion we present a set of original recommendations for developing new applications with potential use in medicine and healthcare.

Keywords. personalized health, medical data, sonification, visualization, warnings

Introduction

The present trends in medicine and healthcare, well-illustrated by the paradigm changes, place in a core position the transition towards individualized medicine – pHealth: personalized, preventive, predictive and participative care [1]. Personalized medicine requires multidisciplinary teams and integrated technologies. The advent of nanotechnologies and the development of more performant wearable and portable devices for health monitoring has brought also an enrichment of signaling and communication tools of these devices. We assist today to a fast increase of solutions based on use of sounds as main or a complementary communication tool. The present paper is dedicated to this new emerging procedure, sonification, and its potential applications in medicine and healthcare.

1. Sonification – Theoretical Background

For most people interested in this domain, the Sonification Handbook edited by Hermann, Hunt and Neuhoff [2] and published in 2011 is the main reference. It is the result of almost two decades of work, partially part of a COST (European COoperation in Science and Technology) Action - IC0601 "Sonic Interaction Design" (SID).

We will limit ourselves here to a brief presentation of the fundamental elements described thoroughly in the cited book and we will then set out some further approaches, with some more details about our three-level approach.

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1.1. Classification of Sonifications

The core notion of this domain is "auditory display", broadly defined as "any display that uses sound to communicate information", while sonification is a subtype, representing only "the use of non-speech audio to convey information or perceptualize data" [3]. Walker and Nees (ch.2 in [2]:9-39) presented two major taxonomic axes for classification of sonifications:

- upon functions of sonification: warnings (alarms, alerts), monitoring (processes, state surveillance), data exploration and entertainment (including art or exercise); we can add here also the function as replacing visual information (e.g. for visually impaired)
- upon sonification approach: event-based, model based and continuous [4].

As observed by Barrass [5], the two axes have a certain degree of convergence – e.g. all warning-type sonifications are event-related. We use the function of sonification taxonomy.

- Warning-type sonifications

There are different quasi-synonymous terms used for this type of sonifications, with some differences:

- alerts or notifications – are sounds to inform the listener that an event has just happened or is going to happen quite soon (microwave beep, doorbell or phone rings)
- alarms or warnings – carry a similar information, most often used for negative or dangerous events and which would require a reaction of the listener (fire alarms, use of sirens during the war, beeps of medical equipment in intensive care units when the heartbeat stops).

The amount of information carried by these signals is not very high, but their value is often very high, which increases their use. In certain cases, the information can be increased: e.g. personalized phone ring tones (set to indicate who is calling). A family of categorical warning sounds in healthcare situations was proposed by Sanderson et al. [6]. Edworthy [7] proposed the use of (helicopter telemetry and avionics) data to modify a given warning sound - "trendsons".

Warning-type sonification duration is usually quite short, yielding a punctual information.

- Sonification for monitoring

In contrast to the warning-type sonification, the applications for following up a process in real time would rather require a sonic display to run in parallel with the process. As any process can be considered as a succession of consecutive states, if each state would have associated an acoustic display segment, the sonification of the process would be dynamically represented by the sequence of the segments aligned along the time axis. We can mention here just some medical applications: Sanderson [6] used such a representation to patient data in an anesthesiologist's workstation, Watson [8] monitored the blood pressure in a hospital environment, Andor et al. [9] monitored the heart rate during exercise in a clinical setting and many others, presented in more detail in the next chapter. Such sequences can be also recorded and replayed at various speed; when replayed fast forward we get a time-compression effect, being able to analyze long duration processes in a short time, while a slow-motion replay can reveal very fast details which might have been skipped in a normal display.

Mihalas et al. [10] have also proposed tempolenses with variable magnification, able to reveal details from the QRS complex of ECG records, but compressing the TP segment. An important advantage of this type of sonification comes from the listener's capacity to detect even small changes of the auditory sequence [2] or when the user has his sight busy with other tasks (for instance while driving, or during surgery).

- Data exploration

The most general sense for the concept of "sonification" is referring to its potential to support data exploration. It is similar to visual inspection of an image or a graph; thus, it would be easy to detect extrasystoles or arrhythmia from a sonic record of the heart rate. Both warning-type and process monitoring type might be considered, to a certain extent, as particular cases of exploration of a set of data. Sonification used for data exploration is meant to offer a holistic view of a system state, a phenomenon or a process, depending on the informational content of the data used, yielding the so-called "soundscapes" [11].

A simple way of approach can be obtained by extension of process monitoring type - similar sonifications have been propsed to represent not only time series but other sequences, like macromolecular structures (nucleotide sequence of DNA or amino-acid sequence in proteins) [12].

In general, any procedure used for graphical data representation might associate a sound track – generating the typical model-based sonifications, the so-called "auditory graphs" [13]. Some interesting solutions have been developed for certain graphs: pie-charts [14] or box-and-whiskers plots [15].

A special attention can be paid to the attempts to transform images into sound. Such an application for medical images was developed by Chiroiu et al. [16]; they have also refined the theoretical formal description of sonification procedures.

- Entertainment, sport and art

The development of gaming industry has stimulated also the sonification area, various methods to associate sounds to events, actions or characters have occurred. They have inspired several applications in other domains, including sports and arts. Some applications in post-traumatic recovery or kinetic therapy have been also enclosed in this class (Hunt and Pauletto, ch.21.2 in [2]:528-531).

Very interesting debates occurred around the question: "can sonification be considered music?", which would be strongly related to the more general topic of "computer music". Indeed, we find so much harmony in living matter, there are so many biological rhythms, so the similarities are not trivial at all. Some sonic motifs found by sonification of natural sequences have already been source of inspiration for musical compositions (John Cage – Music of Changes, 1951 [17], I Xenakis – Metastasis, 1954 [18] etc.) and the interest in this domain is surprisingly high. However, these debates are beyond the scope of this study.

- Replacing visual information

Walker and Ness [2] did not consider replacing visual information as a separate class, including all the applications in the class of entertainment, sports and art, based on similarities with those applications. However, there are specific features for the sonifications used by visually impaired people or external conditions (dark, fog or out-of-sight) which hinders the visual information source. New and very promising results have been developed by mixing sonification with computer vision for the visually impaired people; an example is the soundscape of an "accessible aquarium", which offers information about the location and dynamic movement of fish [19].

The sonification tools of all types presented above, can be included in an integrated system and regarded in the light of the Internet of Things [20].

1.2. Sonification Techniques

Practical considerations lead us to the central problem of sonification - **the correspondence between input data and audio display as output**. Several approaches have been reported, often aiming to solve specific tasks: point or interval estimation, point comparison, trend analysis, identification of data structure or simple exploratory inspection [2]. The variety of proposed relations impose a systematic approach of this topic.

- Interaction degree

Let us consider the degree of interaction allowed to the listener, as described by Hunt and Hermann [21] to build a classification. The simplest algorithms would not let any interaction – it is the non-interactive or „concert mode" when the sonic display is unique, the listener cannot control any parameter. When the user can control some parameters of the correspondence between data and sonic parameters (rhythm, pitch, timbre or many other complex sets) the display is called „conversation mode". These two modes have been also analyzed by Franklin & Roberts [22] who renamed them as "tour based", respectively "query based" sonifications. Usually, various types of "interactions" are designed for extracting specific information, thus we can expect that higher the flexibility to interact higher the usability of a sonification procedure.

- Parameter mapping

Most authors do consider that the algorithms used for parameter mapping represents the basic and characteristic step in sonification. In general terms one has to set values for the characteristics of the sound related to the input data; in other words, parameter mapping sonification is a function, defined on the „data space", with values in the „sound space". We will discuss only a couple of approaches and we will present in more detail the „three-level" approach used in our applications.

The parameter mapping comprises the relations between the data space and the sound space (Figure 1).

- Sonification operator

Chiroiu et al. [16], in their approach to sonify medical images, have started with a sound theoretical introduction comprising a detailed formal mathematical approach: sonification is defined as an „operator to transform the image point data into sound signals"; the input is a time dependent unidimensional string of point data. Application of the sonification operator generates the output sound signal. The set of parameters characterizing the sonification comprised: a factor of time compressor on an interval, a factor of dilation, a reference frequency, two pitch scaling factors, a power distortion factor, an amplitude threshold, a gain factor, a decay parameter and a complex timbre control function. The comprehensive list of parameters offers a great flexibility to apply the sonification operator on a large variety of data. Their results refer to an application on microscopic images of fibrotic rat liver followed by an inverse transformation back into image where some details are better revealed.

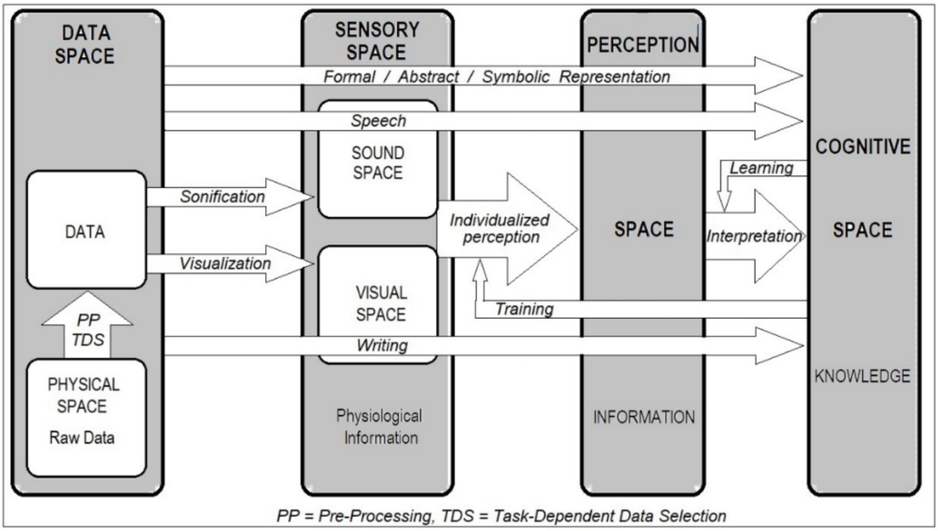

Figure 1. Schematic representation of the sonification process.

- Dimensional analysis

Grond and Berger [23] have made a thorough dimensional analysis of this mapping. Indeed, the definition domain of the sonification function – the data space is characterized by a dimension defined by „all properties directly related to data". Based on other previous work [4], the type of each data of the data domain is also considered – qualitative or quantitative, continuous or discrete and topological structure. The sonification process is split into several steps. First, there is a „data preparation stage, influenced not only by the data structure but also by the sound synthesis parameters of the parameter domain". This step might include a dimensional reduction (e.g. by principal component analysis), or other operations (e.g. derivatives for time series). It also includes the extraction of events (e.g. zero crossing, extremes). The next step - the essence of parameter mapping – is to define the „transfer function which connects the data domain of hard facts with the somewhat more elusive perceptual domain" [24]. The next challenge is to find a good mapping topology (selecting parameters for most appropriate links between data features and perceptual space) [1-4].

- Model-based sonification

We have introduced here the model-based sonification developed by Hermann [25], even its approach is rather different than other mapping modes. The basic starting metaphor - „shake the box" – intuitively suggests that analyzing the reaction / output of a „black box" to a known stimulus / input offers valuable information about the structure and/or function of the system (as used also in the evoked EEG potentials). Thus, model-based sonification is a general framework for designing task-oriented sonifications. Such a design comprises six components: setup, dynamics, excitation, initial state, link-variables, and listener characteristics. The model is built from data space by setup, then, by link variables the information is transferred to the sound space, from which it is extracted via the listener characteristic. The excitation is a feedback action from the listener to the model space.

The importance of the model-based sonification relies in its capacity to address the information from the data space. This approach is suitable for data exploration, mainly for materials structure; we found little reference to medical applications.

A more general mathematical formalization of parameter mapping sonification was done by Rohrhuber [26] covering both direct parameter mapping and model-based sonification.

- The three-level approach

The three-level approach (3L), developed by Mihalas and collaborators [27, 28], tried to keep as main target to address the information to be extracted from the data set but proposing simple mapping functions for practical applications.

a) Paradigm

The main paradigm of the 3L approach starts from the observation that more structured sound output is easier to be understood and interpreted (reproduced, learnt or memorized). Thus, we defined three levels (layers) of the sound space:

- *acoustic* (A) level – similar to the „audification" [3, 25], with a continuum spectrum of frequencies, with either continuous or step-wise transition between two successive sounds;
- *sonic* (S) level, with a discrete spectrum of frequencies (corresponding to musical notes), continuous spectrum of durations;
- *musical* (M) level, introducing harmony and/or rhythm.

b) Data space and pre-processing

The data space comprises all characteristic features of the „sonification object" (system, process) from which the relevant variables are selected; it is specific for each application. The range of variation (and initial values) for each variable should be established.

For most medical applications the data source can be an equipment used for investigations or monitoring, and the data are represented by biological signals. However, there are also several applications where other sources generate the sequences to be sonified (e.g. DNA structure).

The preprocessing comprises usually some common operations (noise reduction, filtering, amplification and normalization); the „clean" signal can be directly sonified or subject to further processing, like event detection, feature extraction or computation of other indicators to be used in sonification (e.g. extraction of heart rate [9, 27] or ST denivelation [29] from ECG recordings).

c) Parameter mapping

After obtaining the sequence to be sonified, the design of the parameter mapping is constructed. In this phase one has to set up the translational parameters vector (reference frequency, sound sampling frequency, pitch scaling factors / ambitus, type of tempolens, compression / dilation factors, channels amplitude ratios etc.) and to define the functions relating sound properties (pitch, duration, loudness, timber) to input data.

- *Pitch.* The audible domain frequency is from 20 Hz to 20 kHz, but the middle range offers the highest sensitivity. That is why most applications take as reference frequency f_0 = 440 Hz (A4 on the musical scale, or MIDI note 69). The hearing scale is exponential (Plack): a double frequency is perceived as on octave higher [30], hence an almost natural relation between the normalized value (y) to be sonified and the frequency (f) of the corresponding sound would be: $f = f_0 * 2\^{}y$. For the acoustic level, the f domain is continuous, while for the S an M levels, f will be rounded to the values from the musical scales, yielding a discrete domain. The ambitus of one octave, offered by this relation can be extended by multiplying the input domain with a factor.

- *Duration*. For applications like real-time process monitoring a 1:1 relation between the duration of the real event and its sonic representation is used. For other applications a compression or dilation factor can be applied. The compression is often used for fast data exploration of long-lasting processes (e.g. listening / reading the ECG monitoring holter records). Important to note that the integrating time for the human ear is around 100 ms [31], hence shorter events / sounds will be rather perceived as clicks, without clear localization of pitch. Important consequences derive from this observation and will be commented in Discussions.
- *Transition type*. The perception is also influenced by the type of transition between two consecutive notes of frequency f_1 and f_2: it can be continuous - traversing all frequencies between the two limits, or step-wise – playing only f_1 and f_2 [27, 32].
- Loudness. Sound intensity is expressed in decibels (dB) and the scale is logarithmic (Webber-Fechner law), spanning from 0 to 120 dB; the perceived loudness is expressed in sons [33] and depends on the frequency. In most sonification applications it is a user adjustable parameter and only relative intensities are information carriers (especially in warning-type sonifications).

d) Sound space

The large diversity of parameter mapping can be further increased by various ways offered by the sound display.

- *Tempolenses*. The compression or dilation factors play a role similar to a tempolens. We have the possibility to replace the constant values of these factors from the sonification parameter vector, with time-dependent functions, obtaining tempolenses with variable magnification, useful in some applications, to reveal details of fast processes and compress or skip less interesting regions [10].
- *Sound artifacts*. The hearing system is pattern-sensitive, hence, not only fundamental sound parameters may be used to convey information from data space but also some simple patterns. Introducing such patterns would represent a step towards the M level; however, we can hardly call music a sequence of two or three beeps. Most common sound artifacts, used especially in warning-type sonifications are the „saccadic" displays – series of 2-3-4 beeps which can represent a scale of warnings. Various intensities may also be added [29, 34].

As our interest was mostly targeted towards information extraction in a simple manner, suggesting staying close to the real data set, as in the acoustic level and simple mappings of the sonic level; we have not developed yet algorithms for the musical level, which introduces more conventional relations.

2. Medical Informatics Meets Sonification / Medical Applications of Sonification

Last decades of the last century marked an increased interest in using sounds to transmit information, as an alternate way to visualization. The potential use of sonification in various applications was documented in several research works. Thus, in 1992, an International Community for Auditory Display was founded, which organizes the annual ICAD conferences since then. The applications cover a variety of topics, including medical topics. The list of applications of sonification in medical domain is very large, a couple of them have already been mentioned in the previous chapter as illustrative examples. It is beyond the scope of this paper to describe these applications in detail; we would rather try to see the major features approached in order to discuss the present state, to compare the achievements with the expectations and to estimate the potential of this domain.

For a systematic browsing of these applications, there are, several taxonomical axes which can be used for their classification:

- upon the type of medical application: diagnosis, treatment, recovery, prevention
- upon the medical discipline: cardiology, neurology, surgery, ICU etc.
- upon the medical / healthcare environment: primary care, hospital, emergency
- upon of type of input data: signals, images, molecular sequences, complex patterns / data sets
- upon the level of projection in the sound space: acoustic (audification), sonic (sonification) or musical level (musification)
- upon the function (task / informational use): warnings, monitoring and therapy, data exploration.

From an informational point of view, the last axis seems the most appropriate, but, for each class, the other criteria will further be affixed.

2.1. Medical Warnings

Warnings represent an important practical way of information transmission encountered in system communication. A comprehensive view can be found in [35], where a special chapter is dedicated to sonification. This class of apps is one of the most useful in medical practice, especially in domains like cardiology, intensive care or emergency units [36, 9]. A thorough analysis was published by Csapó and Wersényi [37], presenting in detail various kinds of alarms: auditory icons (similar to their natural origin – the heart beats, or blood flow in Doppler investigations), earcons (conventional sounds, their use needs a learning phase), spearcons (speeding up speech sounds), auditory emoticons (higher user acceptance than earcons), spemoticons (spearcons of synthesized speech), musicons (brief known musical fragments with associated meaning) and morphocons (earcons customized to user's preferences), useful in applications for visually impaired people. Several authors give present also criteria to be applied when building warnings (chapters 13 and 14 in [2]); Edworthy and Helier [38] recommend refraining from proposing too many alarm types. An excellent set of rules can be found in [39], where the requirements for usable warnings in flight security are described - intensity thresholds, duration, repetitions etc.

2.2. Health Monitoring

These applications cover a multitude of medical specialties. In cardiology, the most monitored variables are the heart rate (Ballora [40], Andor [9, 27]), the ECG signal (Blanco [41], Mihalas [42], Andor [29]) and the pulse wave (Mihalas [10]). In neurology, the EEG signal is the most appropriate signal for sonification (Lutters [43]), while in obstetrics the fetal heart rate variability can be monitored by sonification [44]. More complex systems are used by the anesthesiologists; Fitch and Kramer [45] developed a simulator with eight variables representing patient's vital signs (heart rate, breathing, CO2, temperature, blood pressure, AV dissociation, fibrillation and reflex). A whole range of applications is also found in the field of therapy and recovery. Dozza [46] proposed a portable audio-biofeedback system to improve postural control, Scholz [47] used sonification in stroke rehabilitation, Hunt in [2] in physiotherapy, Vicinanza [48] in sport and rehabilitation. We can include here also the audio devices developed for the visually impaired people [7, 21, 49]. We still expect that the increasing use of portable devices in healthcare will bring also an extension of sonic tools as human-machine interface.

2.3. Medical Data Exploration

Even these applications are not very frequent, they offer the largest variety of mapping solutions. Visi et al. [50] focused on ALS pathophysiology (degenerative amyotrophic lateral sclerosis), Williams and Wilson [51] studied the motility of Plasmodium berghei while Toharia et al. [52] made a musical representation of dendritic spine distribution. Walus et al. [53] explored the use of sonification to support the communication of alcohol health risk in young people. An interesting application was proposed by Legere [54] – use of sonification in managerial decision making. We do include here also the applications presented in the previous chapter: data exploration with auditory graphs [13, 14, 15], sonification of molecular sequences [12, 55]; even the new coronavirus molecular structure has been transposed on sound [56]. A special class is represented by the sonic transform of images [16, 57]; there is even a dedicated software – SoniScan, developed on the Matlab platform.

There are, of course, many other applications; we selected just some examples to demonstrate the variety of sonification applications.

3. Discussions

It is interesting to note that even since the pioneering work, sonification has always been related to its informational value, as seen also from its definition. Barrass [58] developed the concept of Auditory Information Design, emphasizing two elements: „information requirements, which is about specifying information that is useful for a task at hand and information representation, which is about the display of information; ...the intention for generating the sound is to learn something about the data by listening to it; the sound is only regarded as the medium of communication." However, as visible also in fig.1, other communication channels are often used, separately or in parallel, for information representation. We use in practice all channels to get a holistic multimodal representation. The proportion of use of each communication channel is not only specific for each system / process but it also strongly depends on the user, which explains the potential use of sonification in in p-health.

3.1. Sonification vs. Visualization

Several authors who developed various applications did explicitly state that, in most cases, sonification was not meant to replace visualization but to supplement it. Each mode has its advantages to highlight certain informational elements from the data space. Pauletto and Hunt [59] made a thorough comparison between sonification and visualization; the most relevant elements, are summarized in Table.1 [34].

Table 1. Comparative view of dominant characteristics in Visualization vs. Sonification

Property	Visualization	Sonification
Prevalent elements	static	dynamic
Best representation for	spatial distribution	temporal evolution
Better represents	structures	processes
Sensitivity to small differences	low	high
Type of attention needed	focused	distributed
Specific usable properties	color, shape, texture, brightness	timber, rhythm, harmony, loudness

These properties have ensured the realization of most applications developed so far. It is easy to remark the high potential to complement each other in order to accomplish a high-quality perception. It is easy now to understand why most authors did explicitly state in their introduction, that the sonification application proposed is, in most cases, not meant to replace visualization or other type of information representation, but to complement it [60]. (*Why most people like to watch a foreign movie or a TV sports match with original sound on, even the essential information is visually displayed as a text in user's language ?)*

We can also add here the few but important studies focused on the quality of information received by sonification, as the discriminant power yielded by various mappings for the same signal [61, 58/p.34], but the comparison with the discriminant power of visualization was not yet methodically approached.

3.2. Actual State: Between Expectations and Reality

A thorough search through the literature shows that the field of sonification is consolidated, with a sound theoretical foundation, with a well-established community, having already numerous achievements and a series of recognized applications. But, despite these good results, the real impact seemed to be below expectations. Just a few studies included an evaluation of the implementation and the user acceptance. Most often, the applications have not reached the presumed dissemination, the use of the new methods remained rather confined within the producer group. This issue came to the attention of researchers, who tried to analyze the reasons that generated this state [24, 34, 58, 62]. The opinions of different authors were not convergent; the same feature can be both considered as useful (e.g. increasing discriminant power) but also less attractive (e.g. requiring longer training), similar to the inverse relation between sensitivity and specificity of any new tool. We tried to synthesize the discussions from several sources and, without claiming that our list is complete, we can enumerate some of the issues invoked more often:

- Sometimes the resulting sound track is not attractive, even annoying (for acoustic level with continuous transition it sounds like whistles [24]); however, this method is sensitive in comparing two slightly different signals.
- For nonperiodical sequences, in the absence of a real pattern, the „convergence trend" can occur: the listener would have the tendency to classify the heard elements according to his memorized patterns („six rhythm universals") [63].
- The information provided by sonification is redundant with that received by other ways (visualization, speech) [59]; however, this feature ease the learning.
- Almost all proposed solutions require a learning phase [5, 23, 58]; it has been found that more conventional mapping with simple patterns are easier to memorize [34].

Some interactive tools for teaching have been developed [64]; however, several categories of potential users would hardly accept it [24, 62].

– The tremendous variety of sonification modes is utterly confusing; once you open the box of parameter mapping schemes [23-29], a completely new world occurs, with scenes you have never thought about! Each group of authors have developed their own schemes. There were some attempts to classify them, one of the most comprehensive being the survey of Dubus and Bresin [65], who analyzed about sixty sonification mappings. In general terms, an efficient compass to navigate on new territories is offered by standards; but, there are few standards in sonification (the one on MIDI scale is almost irrelevant for practical use in sonification). This feature is, in our opinion, one of the major issues whose solution might become a milestone in sonification future developments; nevertheless, the potential standards should consider all findings in psychoacoustics [33].
– The avalanche of „dedicated" software, to transpose a set of data, as input, in a sonic/musical sequence is another topic which deserve a more extensive discussion. Some programs did offer a high flexibility, attracting larger groups of users; however, they can hardly become standards and we can still ask whether or not they would represent a fence to other most appropriate approaches.
– Several authors had the tendency/ambition to develop an application at the musical level [43, 50-53, 55], introducing conventional harmonies (often) and/or rhythm (rarely); thus, a more pleasant track is obtained, which can divert the user from the main task [34].
– Finally – the sonification approach is still insufficiently known, it is often regarded as a curiosity, being a priori classified as less promising than traditional approaches. Our paper tries to argue that this is a promising topic, which deserves the appropriate attention and support.

3.3. Criteria to Find Potential Bio-Medical Applications of Sonification

The examples and comments made in the previous chapters and paragraphs have already induced the reader several ideas about the cases when sonification can bring, indeed, an improvement of a usual procedure. We fully endorse Kramer's statement (cited in [58]): „Sonification should be heavily task-dependent" [1-5]. The experience accumulated by most cited authors allows a good orientation towards the most prolific work directions:

- all kind of warnings, especially in the context of rapid development of portable/wearable devices; Patel [66] found that synchronization reaction to an audio rhythm is faster and better than the one to a similar visual stimulus. Furthermore, for warnings there are some clear recommendations [35-39], smoothing the way to a better user acceptance;

– cases where the visual system cannot provide full information – it is either busy with other activities (while driving, in the operation theater), or in a special condition (during exercise or darkness);
– applications for categories of people with various disorders - visually impaired people, children with attention deficit (ADHD), elderly people etc.;
– a theoretical feature, still insufficiently explored, would be the use of the tools used in mathematical modelling and computer simulation [67] for developing general mapping schemes;

- a useful application would also be a large database comprising all the reported sonifications, classified on both applicative domain and mapping criteria.
- The list is still open to extensions.

4. Recommendations for Developing Medical Applications of Sonification

For an oral presentation an alternative title would have been „Tips and tricks for ...". Several such „tips" or „hints" have already been slipped among the comments in Discussions. As a conclusion for this study, our recommendations will summarize the major steps in developing an application. It is important to emphasize that sonification is just one of the several ways to transfer information from data space to the perceptual space and it will almost always be just a part of a holistic approach. Some of the steps presented below are similar for starting any new research project and will not be detailed here, paying more attention only to the specific features for sonification.

- Initial steps comprise some well-known actions: define the scope and split it into a couple of objectives; some objectives have classical solutions, but focus on those which need the new approach. Walker and Nees in [2] emphasize this focus („task dependency"), as it helps to select the appropriate data for (pre)processing.
- Build a multidisciplinary team and discuss until the scope and objectives are well defined; analyze the necessary resources and a time frame.
- Try to find one or more solutions for the main problem (parameter mapping - transfer function, in the case of sonification projects); this recommendation might seem in slight contradiction with others' advice who recommend to „read [first] all the papers [on that topic] from the last ten years" [68]. We think that, reading all details of others' work will rather drive you into their kind of thinking and their solutions, perhaps diminishing the potential for new ideas; you may become tributary to classical approaches. This is true especially in domains where, like in sonification, there are few traded paths. Sometimes you need an inspiration, like for a musical composition. Moreover, the literature search becomes more efficient after you have tried yourself to solve the problem. You may find, and it often happens, that other people have already found solutions, maybe similar to yours, but rarely identical, sometimes even more elaborated than yours. One may say that there is no merit in „rediscovering the wheel", but such an exercise is valuable and often this experience will help you in finding further developments. Nevertheless, we have to underline that this recommendation of ours also brings a danger - it can set a trap for you; you think you have found the right solution and you rush to publish it before you read what others have done! Read carefully others' work: start with [60], which will impress you, then [34] for questions and doubts, then [1], then you will be guided to the right reading. Now you can compare your work and hang it at its right place on the list of contributions to the domain.
- Analyze carefully the difference between your initial idea and others' solutions; feel free to dream and use your solutions to extend the usability or performance of others' work.
- If something has not yielded the expected results do not be disappointed – quite often the diamond is covered by mud; try to answer first all „why" questions, and only then the „how" questions.

- Next step - the validation - should include the classical analysis of sensitivity and specificity, which will give you a valuable feedback for further improvements (a well chosen cut-off point can change the balance of false positives and negatives).
- Check the „user acceptance". The history of scientific research is full of projects which have been used mostly by the project team and subsequently the use faded, likely due to the poor analysis of user acceptance. In our opinion, the analysis of user acceptance should have a version to be analyzed prior to the project (similar to market analysis in industry).
- Do not limit yourself to publishing the paper; go to conferences focused on the topic of your interest, meet people with similar concerns, initiate new collaborations, trust in your ideas. Community adoption of a technique or tool is a great measure of success.

The authors hope that the ideas found in this paper will find, to use a musical term - a „resonance" at least among a couple of the readers.

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