TAXONOMY AND DEFINITIONS FOR SONIFICATION AND AUDITORY DISPLAY

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ABSTRACT

Sonification is still a relatively young research field and many terms such as sonification, auditory display, auralization, audification have been used without a precise definition. Recent developments such as the introduction of Model-Based Sonification, the establishment of interactive sonification and the increased interest in sonification from arts have raised the need to revisit the definitions in order to move towards a clearer terminology. This paper introduces a new definition for sonification and auditory display that emphasizes the necessary and sufficient conditions for organized sound to be called sonification. It furthermore suggests a taxonomy, and discusses the relation between visualization and sonification. A hierarchy of closed-loop interactions is furthermore introduced. This paper aims to initiate vivid discussion towards the establishment of a deeper theory of sonification and auditory display.

1. INTRODUCTION

Auditory Display is still a young research field whose birth may be perhaps best traced back to the first ICAD conference[1] in 1992 organized by Kramer. The resulting proceedings volume "Auditory Display" [1] is still one of the most important books in the field. Since then a vast growth of interest, research, and initiatives in auditory display and sonification has occurred. The potential of sound to support human activity, communication with technical systems and to explore complex data has been acknowledged [2] and the field has been established and has clearly left its infancy.

As in every new scientific field, the initial use of terms lacks coherence and terms are being used with diffuse definitions. As the field matures and new techniques are discovered, old definitions may appear too narrow, or, in light of interdisciplinary applications, too unspecific. This is what motivates the redefinitions in this article.

The shortest accepted definition for sonification is from Barrass and Kramer et al. [2]: "Sonification is the use of non-speech audio to convey information". This definition excludes speech as this was the primary association in the auditory display of information at that time. The definition is unclear about what is meant by conveyance of information: are real-world interaction sounds sonifications, e.g. of the properties of an object that is being hit? Is a computer necessary for its rendition? As a more specific definition, the definition in [2] continues:

> "Sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation."

It is significant that the emphasis here is put on the purpose of the usage of sound. This automatically distinguishes sonification from music, where the purpose is not on the precise perception of what interactions are done with an instrument or what data caused the sound, but on an underlying artistic level that operates on a different level. Often, the word 'mapping' has been used interchangeably with 'transformation' in the above definition. This, however, suggests a severe limitation of sonification towards just mappings between data and sound – which was perfectly fine at the time of the definition where such a 'Parameter-Mapping Sonification' was the dominating paradigm.

However, the introduction of *Model-Based Sonification* (MBS) [3, 4] demonstrates methods to explore data by using sound in a way that is very different from a mapping: in Parameter-Mapping Sonification, data values are *mapped* to acoustic attributes of a sound (in other words: the data 'play' an instrument), whereas in MBS sonification models create and configure dynamic processes that do not make sound at all without external interactions (in other words: the data is used to build an instrument or sound-capable object, while the playing is left to the user). The user excites the sonification model and receives acoustic responses that are determined by the temporal evolution of the model. By doing this, structural information is *holistically* encoded into the sound signal, and is no longer a mere mapping of data to sound. One can perhaps state that data are mapped to the configurations of sound-capable objects, but not that they are mapped to sound.

Clearly, sonification models implemented according to MBS are very much in line with the original idea that sonifi-

[1] see www.icad.org

cation allows for the discovery of structures in data through sound. Therefore there is the need to reformulate or adapt the definition for sonification to better include such uses of sound, and beyond that hopefully other possible yet-to-be-discovered linkages between data and sound.

Another challenge for the definition comes from the use of sonification in the arts and music: recently more and more artists incorporate methods from sonification in their work. What implications does this have for the term sonification? Think of scientific visualization vs. art: what is the difference between a painting and a modern visualization? Both are certainly organized colors on a surface, both may have aesthetic qualities, yet they operate on a completely different level: the painting is viewed for different layers of interpretation than the visualization. The visualization is expected to have a precise connection to the underlying data, else it would be useless for the process of interpreting the data. In viewing the painting, however, the focus is set more on whether the observer is being touched by it or what interpretation the painter wants to inspire than what can be learnt about the underlying data. Analogies between sonification and music are close-by.

Although music and sonification are both organized sound, and sonifications can sound like music and vice versa, and certainly sonifications can be 'heard as' music as pointed out in [5], there are important differences which are so far not manifest in the definition of sonification.

2. A DEFINITION FOR SONIFICATION

This section introduces a definition for sonification in light of the aforementioned problems. The definition has been refined thanks to many fruitful discussions with colleagues as listed in the acknowledgements and shall be regarded as a new working definition to foster ongoing discussion in the community towards a solid terminology.

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

(C_1) The sound reflects *objective* properties or relations in the input data.

(C_2) The transformation is *systematic*. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change.

(C_3) The sonification is *reproducible*: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical.

(C_4) The system can intentionally be used with *different data*, and also be used in repetition with the same data.

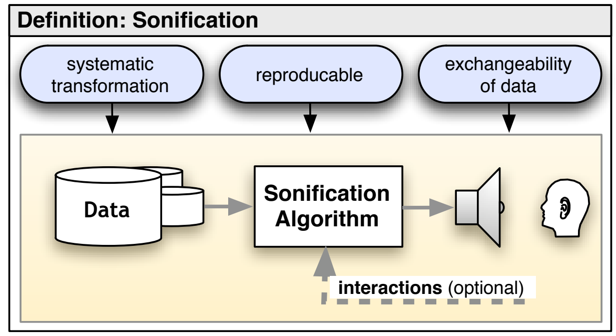

Figure 1: Illustration of the general structure and necessary conditions for sonification. The yellow box depicts besides the sonification elements few other components of auditory displays, see also Sec. 3.

This definition emphasizes important prerequisites for the scientific utility of sonification. It has several partly unexpected implications that are to be explored in the following discussion.

2.1. Discussion

2.1.1. General Comments

Sonification Techniques: According to the above definition, the techniques *Audification, Earcons, Auditory Icons, Parameter-Mapping Sonification* as well as *Model-Based Sonification* are all covered by the definition – they all represent information/data by using sound in an organized and well-structured way and they are therefore different sonification technique.[2] This may first appear unfamiliar in light of the common parlance to see earcons/auditory icons as different from sonification. However, imagine an auditory display for biomedical data that uses auditory icons as sonic events to represent different classes (e.g. auditory icons for benign/malignant tissue). The sonification would then be the superposition or mixture of all the auditory icons chosen for instance according to the class label and organized properly on the time axis. If we sonify a data set consisting only of a single data item we naturally obtain as an extreme case a single auditory icon. The same can be said for earcons. Although sonification originally has the connotation of representing large and complex data sets, it makes sense for the definition to also work for single data points.

Data vs. Information: A distinction between data and information is – as far as the above definition – irrelevant. Think of earcons to represent computer desktop interactions such as "delete file", "rename folder". There can be a lexi-

[2] they are also covered by the definition of sonification as 'non-speech use of sound to convey information'!

con of terms (file, folder, link) and actions (delete, rename, etc.), and in practical computer implementations these features would be represented numerically, e.g. object = O_1, action = A_3. By doing so, the information has been turned into data, and this is generally done if there is more than one signal type to give. Information like for instance a verbal message can always be represented numerically and thus be understood as data. On the other side, raw data values often carry semantic interpretation: e.g. the outside temperature data value -10$°C$ (a one-dimensional data set of size 1) – this is cold, and clearly information! Assuming that information is always encoded as data values for its processing we can deal with both in a single definition. How the data are then represented by using sound is another question: whether sonification techniques use a more symbolic or analogic representation according to the analogic-symbolic continuum of Kramer [6] is secondary for the definition.

Mapping as a specific case of sonification: Some articles have used "sonification" to refer specifically to mapping-based sonification, where data features are mapped to acoustic features of sound events or streams. Yet sonification is more generally the representation of data by using sound. There may be times when a clear specification of the sonification technique, e.g. as model-based, audification or parameter-mapping sonification, may be helpful to avoid confusion with the general term of sonification. It makes sense to always use the most specific term possible, that is to use the term Parameter Mapping Sonification, Audification, Model-Based Sonification, etc. to convey exactly what is meant. The term Sonification, however, is, according to the definition, more general which is also supported by many online definitions[3]. In result we suggest using sonification with the same level of generality as the term visualization is used in visual display.

Sonification as algorithm and sound: Sonification refers to the technique and the process, so basically it refers to the algorithm that is at work between the data, the user and the resulting sound. Often, and with equal right, the resulting sounds are called sonifications. Algorithm means a set of clear rules, independent of whether it is implemented on a computer or any other way.

Sonification as scientific method: According to the definition, sonification is an accurate scientific method which leads to reproducible results, addressing the ear rather then the eye (as visualization does). This does not limit the use of sonifications to data from the sciences, but only states that sonification can be used as a valid instrument to gain insight. The subjectivity in human perception and interpretation is shared with other perceptualization techniques that bridge the gap between data and the human sensory system. Being a scientific method, a prefix like in "scientific sonification" is not necessary.

Same as some data visualizations may be 'viewed' as art, sonifications may be heard as 'music'[5], yet this use differs from the original intent.

2.1.2. Comments to (C_1)

> (C_1) The sound reflects objective properties or relations in the input data.

Real-world acoustics are typically not a sonification although they often deliver object-property-specific systematic sound, since there is no external input data as requested in C_1. For instance, with a bursting bottle, one can identify what is the data, the model and the sound, but the process cannot be repeated with the same bottle. However, using a bottle that fills with rain, hitting it with a spoon once a minute can be seen as a sonification: The data here is the amount of rainfall, which is here measured by the fill level, and the other conditions are also fulfilled. Tuning a guitar string might also be regarded as a sonification to adjust the tension of a string[4]. These examples show that sonifications are not limited to computer-implementations according to the definition, which embraces the possibility of other non-computer-implemented sonifications.

The borders of sonification and real-world acoustics are fuzzy. It might be discussed how helpful it is to regard or denote everyday sounds as sonifications.

2.1.3. Comments to (C_2)

> (C_2) The transformation is systematic. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change.

What exactly do we mean by "precise"? Some sound generators use noise and thereby random elements so that sound events will per se sound different on each rendering. In Parameter-Mapping Sonifications, the intentional addition of noise (for instance as onset jitter to increase perceptability of events that would otherwise coincide) is often used and makes sense. In order to include such cases randomness is allowed in the definition, yet it is important to declare where and what random elements are used (e.g. by describing the noise distribution). It is also helpful to give a motivation for the use of such random elements. By using too much noise, it is possible to generate useless sonifications in the sense that they garble interpretation of the underlying data. In the same way it is possible to create useless scientific visualizations.

[3] http://en.wikipedia.org/wiki/Sonification, http://wvvel.csee.wvu.edu/sepscor/sonification/lesson9.html, http://www.techfak.uni-bielefeld.de/ags/ni/projects/datamining/datason/datason_e.html, http://www.cs.uiowa.edu/ kearney/22c296Fall02/ CrittendonSpecialty.pdf, to name a few.

[4] thanks to the referee for this example!

2.1.4. Comments to (C_3)

(C_3) The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical.

The definition claims reproducibility. This may not strictly be achieved for several reasons: the loudspeakers may generate a different sound at different temperatures, other factors such as introduced noise as discussed above may have been added. The use of the term "structurally identical" in the definition aims to weaken the stronger claim of sample-based identity. Sample-based identity is not necessary, yet all possible psychophysical tests should come to identical conclusions.

2.1.5. Comments to (C_4)

(C_4) The system can intentionally be used with different data, and also be used in repetition with the same data.

Repeatability is essential for a technique to be scientifically valid and useful – otherwise nobody could check the results obtained by using sonification as instrument to gain insight. However, there are some implications by claiming repeatability for what can and cannot be called sonification. It has for instance been suggested that a musician improvising on his instrument produces 'a sonification of the musician's emotional state'. With C_4, however, "playing a musical instrument" is not a sonification of the performer's emotional state, since it can not be repeated with the 'identical' data. However, the resulting sound may be called a sonification of the interactions with the instrument (regarded here as data), and in fact, music can be heard with the focus to understand the systematic interaction patterns with the instruments.

Some of these conditions have been set as constraints for sonification, e.g. reproducibility in the 'Listening to the Mind Listening' concert[5], but not been connected to a definition of sonification.

In summary, the given definition provides a set of necessary conditions for systems and methods to be called sonification. The definition is neither exhaustive nor complete; we hope it will serve as the core definition as we as community work towards a complete one.

3. SONIFICATION AND AUDITORY DISPLAY

With the above definition, the term sonification takes the role of a general term to express the method of rendering sound in an organized and well-structured way. This is in good analogy with the term *visualization* which is also the general term under which a variety of specific techniques such as bar charts, scatter plots, graphs, etc. are subsumed. Particularly there is an analogy between *scatter plots* where graphical symbols (data-mapped color/size...) are organized in space to deliver the visualization, and *Parameter-Mapping Sonification*, where in a structurally identical way acoustic events (with data-mapped features) are organized in time. It is helpful to have with sonification a term that operates on the same level of generality as visualization.

This raises the question what then do we mean by auditory displays? Interestingly, in the visual realm, the term 'display' suggests a necessary but complementary part of the interface chain: the device to generate structured light/images, for instance a CRT or LCD display or a projector. So in visualization, the term *visualization* emphasizes the way how data are rendered as an image while the *display* is necessary for a user to actually see the information. For auditory display, we suggest to include this aspect of conversion of sound signals into audible sound, so that an auditory display encompasses also the technical system used to create sound waves, or more general: all possible transmissions which finally lead to audible perceptions for the user. This could range from loudspeakers over headphones to bone conduction devices. We suggest furthermore that auditory display should also include the user context (user, task, background sound, constraints) and the application context, since these are all quite essential for the design and implementation. Sonification is thereby an integral component within an auditory display system which addresses the actual rendering of sound signals which in turn depend on the data and optional interactions, as illustrated in Fig. 2. Auditory Displays are more comprehensive than sonifica-

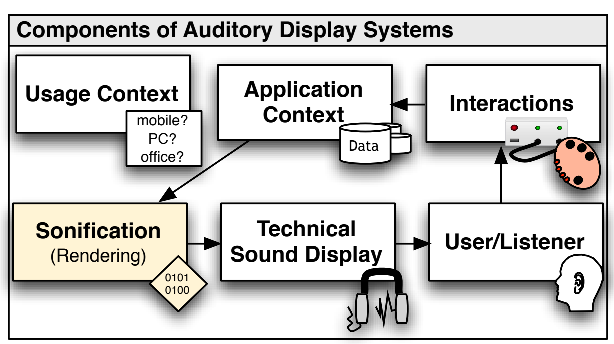

Figure 2: Auditory Displays: systems that employ sonification for structuring sound and furthermore include the transmission chain leading to audible perceptions and the application context.

[5]http://www.icad.org/websiteV2.0/Conferences/ICAD2004/concert_call.htm

tion since for instance dialogue systems and speech interfaces may also be regarded as auditory displays since they use sound for communication. While such interfaces are not the primary focus in this research field the terminology suggests their inclusion. On the other hand, Auditory Display may be seen as a subset of the more general term of *Auditory Interfaces* which do not only include output interfaces (auditory displays, sonification) but also auditory input interfaces which engender bidirectional auditory control and communication between a user and a (in most cases) technical system (e.g. voice control system, query-by humming systems, etc.).

4. HIERARCHY FROM SOUND TO SONIFICATION

So far we have dealt with the necessary conditions surrounding sonification and thus narrowed sonification down to a specific subset of using sound. In this section, we look at sonification in a systemic manner to elucidate its superordinate categories. Figure 3 shows how we suggest to organize the different classes of sound. On the highest level,

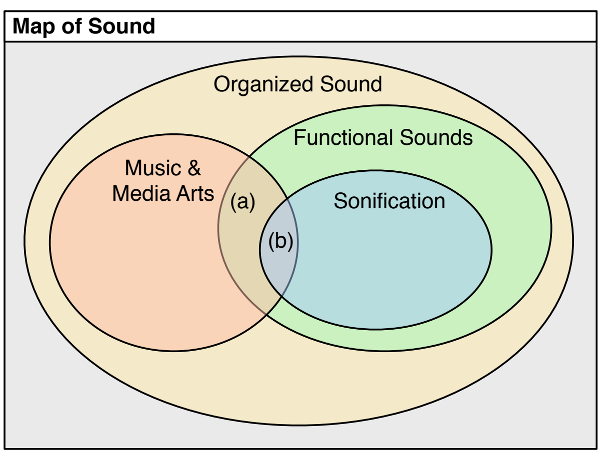

Figure 3: Systemic map of sound, showing sonification and its relation to other categories.

sounds are here classified as *Organized Sound* and unorganized sound. Organized sounds separate from random or otherwise complex structured sounds in the fact that their occurence and structure is shaped by intention. Environmental sounds appear often to be very structured and could thus also be organized sounds, however, if so, any sound would match that category to some extent. It thus may be useful to apply the term to sounds that are intentionally organized – in most cases by the sound/interface developer.

The set of organized sound comprises two large sets that partially overlap: music and functional sounds. Music is without question a complex structured signal, organized on various levels, from the acoustic signal to its temporal organization in bars, motifs, parts, layers. It is not our purpose to give a definition of music.

The second set is functional sounds. These are organized sounds that serve a certain function or goal [7]. The function is the motivation for their creation and use. To give an example, all signal sounds (such as telephones, doorbells, horns and warning hooters) are functional sounds. Certainly there are intersections with music, as music can serve functional aspects. For instance, trombones and kettle drums have been used to demonstrate kingship and power. A more subtle function is the use of music in supermarkets to enhance the ‘shopping mood’. For that reason these sets overlap – the size of the overlap depends on what is regarded as function.

Sonification in the sense of the above definition is certainly a subset of functional sounds. The sounds are rendered to fulfill a certain function, be it communication of information (signals & alarms), the monitoring of processes, or to support better understanding of structure in data under analysis. So is there a difference between functional sounds and sonification at all? The following example makes clear that sonification is really a subset: Recently a new selective acoustic weapon has been used, the mosquito device[6], a loudspeaker that produces a HF-sound inaudible to older people, which drives away teenagers hanging around in front of shops. This sound is surely functional, yet it could neither pass as sonification nor as music.

Finally, we discuss whether sonification has an intersection with music&media arts. Obviously there are many examples where data are used to drive aspects of musical performances, e.g. data collected from motion tracking or biosensors attached to a performer. This is, concerning the involved techniques and implementations similar to mapping sonifications. However, a closer look at our proposed definition shows that often the condition for the transformation to be systematic C_2 is violated and the exact rules are not made explicit. But without making the relationship explicit, the listener cannot use the sound to understand the underlying data better. In addition, condition C_4 may often be violated. If sonification-like techniques are employed to obtain a specific musical or acoustic effect without transparency between the used data and details of the sonification techniques, it might, for the sake of clarity, better be denoted as ‘data-inspired music’, or ‘data-controlled music’ than as sonification. Iannis Xenakis, for instance, did not even want the listener to be aware of the data source nor the rules of sound generation.

[6]see http://www.compoundsecurity.co.uk/, last seen 2008-01-16

5. CLOSED INTERACTION LOOPS IN AUDITORY DISPLAYS

This section emphasizes the role of interaction in sonification. We propose different terms depending on the scope of the closure of the interaction loop. The motivation for this discussion is that it might be helpful to address how terms such as biofeedback or interactive sonification relate to each other.

We start the discussion with Fig. 4 that depicts closed loop interactions. The sonification module in the upper center playing rendered sonifications to the user. Data sources for sonification enter the box on the left side and the most important parts are (a) World/System: this comprises any system in the world that is connected to the sonification module, e.g. via sensors that measure its state, and (b) Data: these are any data under analysis or represented information to be displayed that are stored separately and accessible by the sonification.

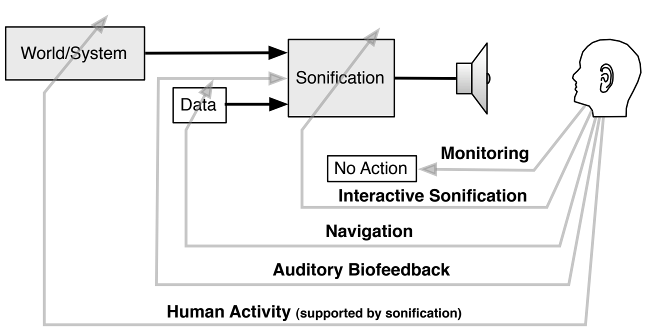

Figure 4: Illustration of Closed-Loop Auditory Systems.

In this setting, **Process Monitoring** is the least interactive sonification, where data recorded from the world (in real-time) or read from the data repository is continuously used as input for a sonification rendering process. Here, the listener is merely passively listening to the sound with the only active component being his/her focus of attention onto parts of the sound. Certainly, certain changes in the sound might attract attention and force the user to act (e.g. sell stocks, stop a machine, etc...).

A higher degree of active involvement occurs when the user actively changes and adjusts parameters of the sonification module, or interacts otherwise with the sonification system. We denote this case as **Interactive Sonification**. There is a wide field of possibilities of why and how to do so, and we discuss 3 different prototypical examples:

(a) *Triggering*: Consider a mapping sonification of a given data set. An essential interaction for the user is to issue the command to render/playback the sonification for a selected dataset. Possibly he/she does this several times in order to attend different parts of the sound signal. This elementary case is an interaction, however, a very basic one.

(b) *Parameter Adjustment* is done when the user changes parameters, such as what data feature are mapped to acoustic parameters, control ranges, compression factors, etc. Often such adjustments happen separate from the playback so that the changes are made and afterwards the updated sound is rendered. However, interactive real-time control is feasible in many cases and shows a higher degree of interactivity. The user actively explores the data by generating different 'views' of the data [8]. In visualization a similar interactivity is obtained by allowing the user to select axes scalings, etc.

(c) *Excitatory Interaction* is the third sort of interaction and is structurally similar to the case of triggering. Particularly in *Model-Based Sonification* [4], usually the data are used to configure a sound-capable virtual object that in turn reacts on excitatory interactions with acoustic responses whereby the user can explore the data interactively. Excitation puts energy into the dynamic system and thus initiates an audible dynamical system behavior. Beyond a simple triggering, excitatory interactions can be designed to make use of the fine-grained manipulation skills that human hands allow, e.g. by enabling to shake, squeeze, tilt or deform the virtual object, for instance using sensor-equipped physical interfaces to interact with the sonification model. A good example for MBS is Shoogle by Williamson et al. [9], where short text messages in a mobile phone can be overviewed by shaking a mobile phone equipped with accelerometer sensors, resulting in audible responses of the text messages as objects moving virtually inside the phone. Excitatory interactions offer rich and complex interactions for interactive sonification.

The next possibility for a closed loop is by interactions that select or browse data. Since data are chosen, it may best be referred to as **Navigation**. Navigation can also be regarded as special case of Interactive Sonification, depending on where the data are selected and the borders are here really soft. Navigation usually goes hand in hand with triggering of sonification (explained above).

Auditory Biofeedback can be interpreted as a sonification of measured sensor data. In contrast to the above types, the user's activity is not *controlling* an otherwise autonomous sonification with independent data, but it produces the input data for the sonification system. The user perceives a sound that depends on his/her own activity. Such systems have applications that range from rehabilitation training to movement training in sports, e.g. to perform a complex motion sequence (e.g. a tennis serve) so that its sonification is structurally more similar to the sonification of an expert performing the action [10].

The final category is **Human Activity**, which means that the interaction ranges beyond the sonification system into the world, often driven by the goal to change a world state in a specific way. In turn, any sensors that pick up the change may lead to changes in the sonification. The difference between the loop types before is that the primary focus is to achieve a goal beyond the sonification system, and *not* to interact with a closed-loop sonification system. Even without attending the sonification consciously or primarily, the sound can be helpful to reach the goal. For example, imagine the real-world task to fill a thermos bottle with tea. While your primary goal is to get the bottle filled you will receive the 'gluck-gluck' sound with increasing pitch as a by-product of the interaction. If this is consistently useful, you subconsciously adapt your activity to exploit the cues in the sound – but the sound is only periphery for the goal. In a similar sense, sonifications may deliver helpful by-products to actions that change the world state. We regard such *interaction add-ons* where sonification is a non-obtrusive yet helpful cue for goal attainment as inspiring design direction. Such sonifications might even become subliminal in the sense that users, when asked about the sound, are not even aware of the sound, yet they perform better with sound than without.

6. DISCUSSION AND CONCLUSION

The definitions in this paper are given on the basis of three goals: (i) to anchor *sonification* as a precise scientific method so that it delivers reproducible results and thus can be used and trusted as instrument to obtain insight into data under analysis. (ii) to offer a generalization which does not limit itself to the special case of mappings from data to sound, but which introduces sonification as general systematic mediator between data and sound, whatever the representation might be. (iii) to balance the definition so that the often-seen pair of terms 'visualization & sonification' are at the same level of generality.

The definition has several implications which have been discussed in Sec. 2. We'd like to emphasize that this effort is being done in hope that the definition inspires a general discussion on the terminology and taxonomy of the research field of auditory display. An online version of the definition is provided at www.sonification.de with the aim to collect comments and examples of sonifications as well as examples that are agreed *not* to be sonifications and which help in turn to improve the definition.

In Section 3, we described integral parts for auditory display so that sonification takes a key component as the technical part involving the rendition of sound. Again, the suggested modules are meant as working hypothesis to be discussed at ICAD.

While the given definitions specified terms on a horizontal level, Section 4 proposes a vertical organization of sound in relation to often used terms. The intersections between the different terms and categories have been addressed with examples.

Finally, we have presented in Section 5 an integrative scheme for organizing different classes of auditory closed loops according to the loop closure scope. It proves helpful to clarify classes of interactive sonifications. We think that grouping existing sonifications according to these categories can be helpful to better find alternative approaches for a given task.

The suggested terminology and taxonomy is the result of many discussions and a thorough search for helpful concepts. We suggest it as working definitions to be discussed at the interdisciplinary level of ICAD in hope to contribute towards a maturing of the fields of auditory display and sonification.

7. ACKNOWLEDGEMENT

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