Marshall Plan Scholarship Report

Collaborative Sonification Design to Sonify Scientific Data

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AKNOWLEDGMENT

I would like to take the opportunity to express my appreciation for Austrian Marshall Plan Foundation for providing this scholarship to make the inter-university research possible. Staying at Stanford University assisted me to take my research goals many steps deeper by using other facilities and having the brain-storming sessions with amazing students and professors of Center for Computer Research in Music and Acoustics (CCRMA) at Stanford.

The scholarship would have been unknown and unavailable to me, were it not be introduced to me by (Institute of Electronic Music and Acoustics in Graz University of Music and Performing Arts) IEM's director Dr. Alois Sontacchi. Special thanks to Dr. Sontacchi for giving me invaluable advice on how and when to apply for the scholarship successfully. I am incredibly appreciative of Professor Jonathan Berger for his great efforts in my research development during my stay with his institution and his effort to make my time at Stanford a great success. Professor Höldrich also, as always, provided me with guidance during my stay through Skype and emails and gave feedback on my research.

Thanks to my family and friends on both continents who made my move back and forth between US and Austria possible.

Parts of this report is already published.

1 INTRODUCTION

In this report I introduce the research question, the methods I used to answer some of the research questions, and finally the components of the project that were suitable to work on at Stanford University during my research fellowship. In the next chapters I introduce the HCI field in general and then in specific the building blocks I used to utilize HCI process in the field of Auditory Display in a collaborative and participatory way.

The amount of data being processed today is steadily increasing, and both scientists and society need new ways to understand scientific data and their implications. Sonification – the use of sound to convey information about data- is especially suited to the preliminary exploration of complex, dynamic, and multidimensional data sets such as climate data. These kind of large and multivariate time-based data sets, are gathered both from empirical satellite provided sources as well as models.

Scientists in different domains (henceforth domain scientists) usually focus on vision when interpreting their data. Visual display is regarded as the predominant and most appropriate data representation in our society . For 20 years, a different type of data representation has been studied: sonification, the auditory analogue to visualisation. From everyday listening experience we—as human beings—are well trained in resolving complex sounds. Thus, the sonification of high-dimensional data, where full visualisation is not possible, has great potential to be explored. Sound is still a rather new medium of information in the sciences, and specified auditory tools are largely missing. In scientific data display, sonification may provide new 'viewpoints' and enable the researchers to formulate innovative hypotheses. Furthermore, sound is an ideal medium for communication about science, due to its highly affective nature. Consequently, sonifications are often found in collaborations between science and art or they are used in media-installations for didactic purposes.

In an on-going research project (name and link blinded for review), climate data are sonified following a mainly scientific focus. The project aims at providing both new case studies for large-scale sonification examples as well as a new, user-centred approach for developing sonifications in general.

Climate data provide a good working basis for sonifications. Both model data and measured data are at hand, and the data are less abstract than in other scientific domains, thus providing a straightforward real-world interpretation. Often, a complete visualisation is impossible, because the data sets are high dimensional and large. This generates opportunities for innovative data displays, as has been explored for innovative visualisation ,but also opens a potential for auditory displays. Finally, there is consensus on global climate change and the necessity of intensified climate research today in the scientific community and general public. Sonification may provide a new means to communicate scientific results and inform a wider audience.

In my research project SysSon, I apply a systematic approach to design sonifications of climate data. In collaboration with the Wegener Center for Climate and Global Change, I assessed the parameters climate scientists use and their typical workflows. This background was used to design and develop a multi-modal interface, which is integrated with the visualisation tools the scientists use already for data analysis. A sonification platform is built and will be evaluated according to its functionality and usability for climate scientists, as well as under aesthetic criteria. In the current stage of the project, conceptual links between climate science and sound have been elaborated and first sonification designs have been developed.

Similar to the visual system, the human hearing system possesses high-level pattern recognition, as Bregman reported in Auditory Scene Analysis. Regarding temporal resolution and frequency range, the ear exceeds by far visual capabilities: while movies usually show 24 frames per second which is sufficient to successfully simulate continuous evolution, the “ear” is able to resolve temporal microstructures of a magnitude of a few milliseconds. And while we can hear pitches across 10 octaves (from 20Hz to 20kHz, demanding a sampling rate of more than 40kHz for high-quality digital audio), we see only one “octave” (400–700nm). Kramer was the first to outline the advantages of auditory display (AD): Eyes-free conditions allow monitoring tasks or multi-modal displays. “Backgrounding” is a psycho-acoustical effect where permanent stimuli are faded out, while any change in sound is immediately detected (alerting). The ear facilitates orientation in all spatial directions, while the eyes only see ahead. Auditory scene analysis allows the perceptual separation of simultaneous auditory streams. However, AD also has some drawbacks. Its parameters lack strict orthogonality, for example pitch and amplitude are not perceptually independent: higher pitched-sounds are perceived as louder than lower ones. Many parameters exhibit relatively low resolution for untrained listeners and are not suitable for the display of absolute values (e.g., pitch). Finally, aesthetics plays an important role in AD, as sound can easily become annoying.

Art is often ahead of its time and has a pioneering role, which has inspired scientific development in many cases. Early artistic sonification examples can be found in 20th century composition and media art: for instance, John Cage “sonified” the starlit sky in 1962, by superimposing staves on star charts and thus treating the stars as note heads in his piece “Atlas Eclipticalis”. Alvin Lucier, in his “Music for Solo Performer“ in 1965, used the alpha brain waves of his EEG signal to trigger percussion instruments. Today, the artist and researcher A. Polli uses sonification of weather and climate phenomena in her work, and M. Quinn focuses on scientific outreach of climate by using sonification for creating music. What follows from these artistic examples, is that sonification is an interdisciplinary endeavour, in which both analytic and aesthetic knowledge of sound is needed. The pioneer of sonification research, G. Kramer commented in [4] that, “if the sound is ugly, people won’t use it.” Today, the difference between scientific sonification and sonification as sound/ media art is one of intention, as discussed by St. Barrass. Sonification can be understood as the intersection of functional sounds and aesthetical use of sound in the media arts.

Then, why are sonifications not applied more widely today? Different reasons can be found. Visual display has been given a head start of some hundred years of research and standardization. It has been incorporated into teaching at all levels, starting from elementary school. The result is a cultural bias towards an assumed objectivity of visual displays that is reflected in language: to cite only one example, we say “I see” when we understand something, while “knowing from hearsay” is a dismissive statement. Furthermore, sonification research has often been conducted out of private enthusiasm of a few pioneers’ world-wide, situations where quality control or usability were not considered in detail due to limited budget and time. Finally, only in the last ten years has the soft- and hardware needed for high-quality sound reproduction become available to the majority of work places of different target disciplines. The main goal of our research project is to tackle the above-mentioned obstacles. As case study, we chose to sonify data from climate science.

The current prototype is an interactive sonification tool, which combines a workspace for the scientists with a development environment for sonification models. The tool runs on different operating systems and is released as open source. In the standalone desktop application, multiple data sources can be imported, navigated and manipulated either via text or a graphical interface, including traditional plotting facilities. Sound models are built from unit generator graphs, which are enhanced with matrix manipulation functions. They allow us to systematically experiment with elements known from the visual domain, such as range selections, scaling, thresholding, markers and labels. The models are organized in an extensible library, from which the user can choose and parametrize. Importance is given to the persistence of all configurations, in order to faithfully reproduce sonification instances.

Contextual task analysis is an established technique in Human Computer Interaction, therefore we decided to explore different data analysis tasks that climate scientists are regularly involved in. The approach is challenging because each scientist uses an individual set of programs and performs different tasks, due to different habits and background. Therefore we conducted a usability study in a non-classical sense as well. In a field study an observer and an interviewer visited climate scientists in their workplace to capture their workflows, and the environmental factors while analysing data. Following a questionnaire they assessed the general questions and marked if all relevant topics have been covered during the open task. Interviews took about an hour and consisted of three parts. The central part of the individual interview session consisted of a walk-through of a self-chosen data analysis task. Finally, expectations about an auditory display were collected, including a recording of what the data in the task would sound like, which data sets would be most useful for the participants to sonify, and how and if they would use sound at their work. Focus groups were conducted to observe more specific information about the communication between the experts. Participants belong to three different research groups. Participants brought their own task results, as had been demonstrated in the contextual inquiry, and were asked to briefly present and discuss them with the other members of the group.

Afterwards, in two sets of case studies, the climate scientists and audio experts were asked to pair sound stimuli with climate terms extracted from the first interviews and evaluate the sound samples aesthetically. They were asked to choose sound textures (from a set of sounds given to them) that best express the specific climate parameter and rate the relevance of the sound to the metaphor. Throughout these studies, correlations between climate terminology and sound stimuli for the sonification tool are assessed to improve the sound design.

A main outcome of the extensive analysis of the contextual inquiry is improving our understanding of the way climate scientists work, communicate, and think. The next questions needs to be answered are wether a collaborative sonification design improves the quality of the tool and how the exchange across disciplines works under time pressure. In order to answer these questions, multiple sonification workshops and trainings are planned to allow domain scientists work in cross-disciplinary teams with the sonification experts on designing sonification algorithms.

The next steps that are explored at Stanford with audio experts are parameterisation and magnitude estimation in the platform. Furthermore, the results from collaborative training sessions are qualitatively and quantitatively analysed during the stay at Stanford. Getting feedback from mentors at Stanford was also very beneficial to evaluate the results from training sessions and workshops.

2 DATA ANALYSIS AND DATA SONIFICATION

2.1. MOTIVATION

The widespread digitalization of almost all aspects of our lives and the rapid growth of electronically stored data in the Internet has necessitated methods to process data and extract knowledge from them. The main concern has been how the interface between humans and computers can be improved to support discerning meaningful data (data mining) and extracting knowledge. The two approaches of data mining are machine learning and exploratory data analysis. In the former, computers are given perceptual abilities to detect features and structures within high-dimensional datasets. In the latter, human-computer interfaces are built to allow data scientists to explore complex data and better understand relations and patterns in them. Visual displays have been used as the primary tool in this process.

The purpose of this chapter is to elaborate an understanding of what data is as a concept, as a component in acquisition of knowledge, and as something that can be communicated between its source and its receiver in visual and auditory form. In the contact of designing, developing, and evaluating software tools that enable such communication, having an understanding of some of the principals involved in data mining such as exploratory and confirmatory data analysis is worthwhile. Furthermore, theoretical framework for common visualization techniques and statistical graphics is investigated. In order to understand sonification properly, a section is dedicated to human's auditory and visual senses, their benefits and shortcoming, and how they complement one another. In particular, the focus is on the auditory perception and to develop techniques which allow to present data in form of sound. Finally, some sonification frameworks that are used for data analysis tasks and challenges for using them are discussed.

As an exemplar the use of data mining and sonification in the context of a data-intense domain such as climate science is explored. Climate data sets used throughout this thesis are described in details in Appendix I, but where necessary the data features used in the examples are outlined in the context of the chapter. The goal is to improve the climate scientists' knowledge about features and patterns hidden in the data. Climate data is an ideal domain for a number of reasons including the typically large multivariate data sets, the dynamically changing nature of the data, and the nature and process of creating models. Climate science data is usually temporal, spatial, or spatiotemporal which makes it a perfect candidate for data mining and sonification.

While there is decades of research in climate science and applications of auditory display in data science, systematic efforts in user centered design approaches for sonification of climate science are rare. Some aspects of data analysis that are interesting to explore are: how to deal with auto- or cross-correlations. Climate data are geographical and inherit the spatial or temporal correlation properties. Additional challenges in sonification of climate data stem from nonlinear dependence, long memory processes in time, and long-range dependence in space.

2.2. DATA MINING AND KNOWLEDGE DISCOVERY

The rapid development of information technology in the recent decades has exposed every field in science and technology to data-rich disciplines and entailed the development of methods and tools to analyse huge amount of data and extract useful information from the rapidly growing volumes of digital data. The rate of data generation and storage far exceeds the rate of data analyses which could cause loss of scientific insights in data. Thus, the use of new ways of data mining and knowledge discovery such as machine learning, pattern recognition, information retrieval, visualisation, and sonification, has become crucial.

Data mining helps to search through huge amounts of data in order to find patterns and trends. According to Fayyad, Data mining, the analysis step of the "Knowledge Discovery" process [FS96], an interdisciplinary subfield of computer science, is the computational process of discovering patterns in large data sets involving methods at the intersection of artificial intelligence, machine learning, statistics, and database systems. Hastie et al. [Has05] delineate the overall goal of the data mining process as extraction of information from a data set and transforming it into an understandable structure for further use.

Knowledge Discovery is the process of identifying viable, novel, useful, and understandable pattern in data. Fig.2.1 illustrates the steps that construct knowledge discovery process according to Fayyad [FPS96].
Fayyad’s overall process of finding and interpreting patterns from data involves the application of the following steps iteratively:

- Developing an understanding of the application domain, the relevant prior knowledge, and the goals of the user.
- Creating a target data set: selecting a data set, or focusing on a subset of variables, or data samples, on which discovery needs to be performed.
- Data cleaning and preprocessing: removal of noise or outliers, handling missing data fields, accounting for time sequence information and known changes.
- Data reduction and projection: finding useful features to represent the data depending on the goal of the task, using dimensionality reduction or transformation methods to reduce the effective number of variables under consideration or to find invariant representations for the data.
- Choosing the data mining task: deciding whether the goal of the KDD process is classification, regression, clustering, etc.
- Choosing the data mining algorithm(s): selecting method(s) to be used for searching for patterns and structures in the data, deciding which models and parameters may be appropriate, matching a particular data mining method with the overall criteria of the KDD process.
- Data mining: searching for patterns of interest in a particular representational form or a set of such representations as classification rules or trees, regression, clustering, etc.
- Interpreting mined patterns.
- Combining discovered knowledge.

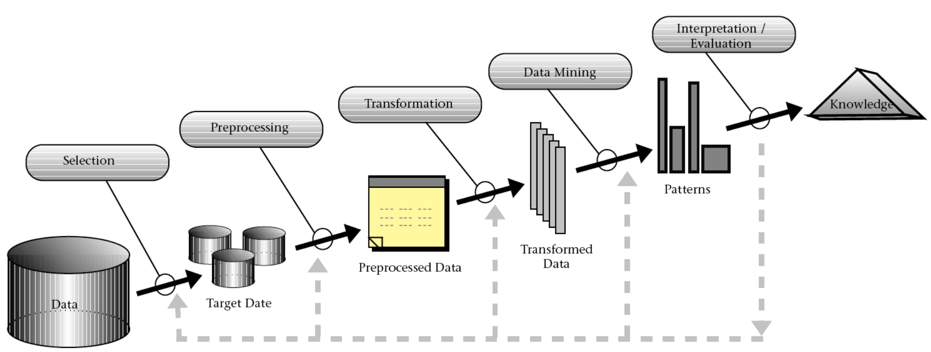

Figure 2.1 Overview of the steps that compose Knowledge discovery process [Fayyad et al. 1996]

The Knowledge Discovery approach is interactive and iterative involving numerous steps with many decisions made by user. Brachman and Anand [BA96] give a practical view of this process, emphasising the interactive nature of it. In data analysis it is essential to avoid data dredging; which is the blind application of data mining methods that could lead to discovery of meaningless and invalid patterns in data.

According to Hand et. al [HHP01] exploratory data analysis (EDA) is data-driven hypothesis generation. In EDA, the data is observed, in search of structures to reveal broader relationships between variables. Exploratory techniques may be used to find an indication to the correct hypothesis to test based on a set of data. This process contrasts hypothesis testing or confirmatory data analysis (CDA), which begins with a suggested model or hypothesis and undertakes statistical manipulations to determine the likelihood that data arose from such a model.

Looking for patterns in data and finding hypotheses to test by visual representations of data systematically is introduced by Tukey in Exploratory Data Analysis [Tuk70]. According to Tukey, for a set of univariate observations there are several pieces of evidence that exploratory data analysis may find:

- the midpoint of the data, the shape and spread;
- the range and ordering of the data, describing the span between the highest and lowest values in the data, and the sorting of the data point values between these two extremes;
- the outliers in the data, the data points that do not follow the data's general pattern and may indicate aberrations or perhaps significant points of interest;
- the relationships between variables in the data, focusing on factors that explain or determine the variability in the data.

CDA data mining types of tasks could be categorised in:

- Descriptive Modelling: The goal in this modelling is to describe all of the data or the process that generates the data with a model. For example density estimation for the overall distribution of data, cluster analysis and segregation to partition data into groups, dependency modelling to describe the relationship between the variables.
- Predictive modelling: Classification and Regression: The goal in this model is to predict the value of one variable from the known value of

other variable. In classification the variable being predicted is categorical, while in regression it is quantitative.

- Discovering Patterns and Rules: when data mining is not involved in model building, it is used for pattern recognition.

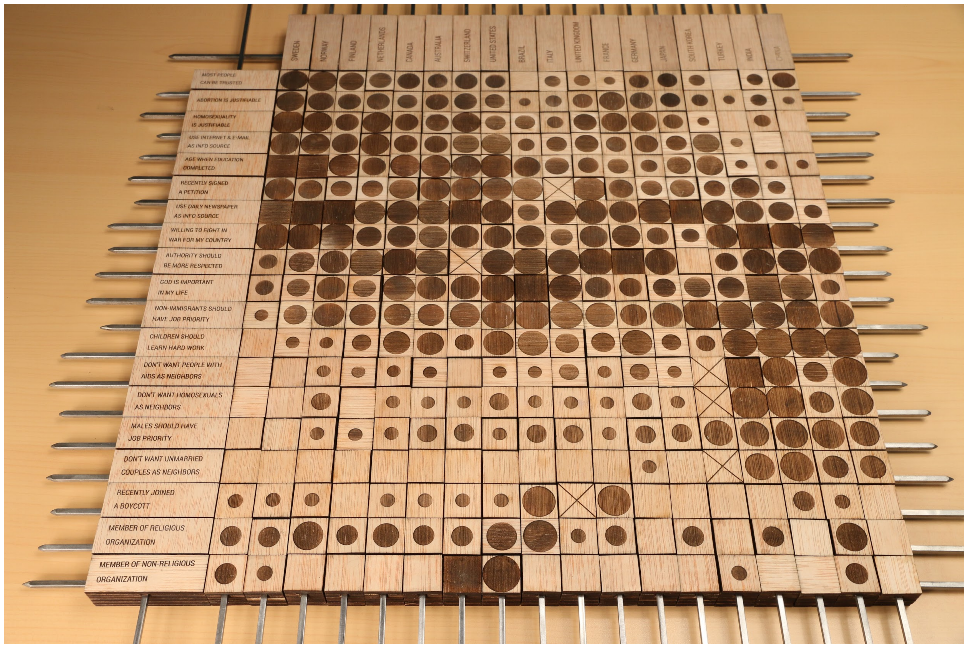

Fig.2.2. A large-scale replica of Jacques Bertin's physical matrices that he called Domino, source: [PLD+15]

Bertin [Ber81] developed the permutation matrix to analyse data. Bertin matrices allow rearrangements to transform an initial matrix to a more homogeneous structure. He argued that all representations of data are reducible to a single matrix. Tufte [Tuf83] was also very influential in using graphics as main method for analysing and reasoning about data and highlighting of the importance of design features in the efficiency of information graphics. He emphasises the graphics that ‘Above all else, show the data’; which usefully communicate the story the data entails and criticises decorative graphics. On the other hand, Bateman et al. [Bat10] find decorative graphics such as elaborated borders, cartoon elements, and 3-d projections useful. They conducted experiments that compared embellished charts with plain ones, and measured interpretation accuracy and long term recall and they found that people’s accuracy in describing embellished charts were no worse than for plain charts, and that their recall was significantly better by embellished charts. Fig.2.3 is an example of charts used in their study. Embellished version on the left and equivalent plain version on the right.

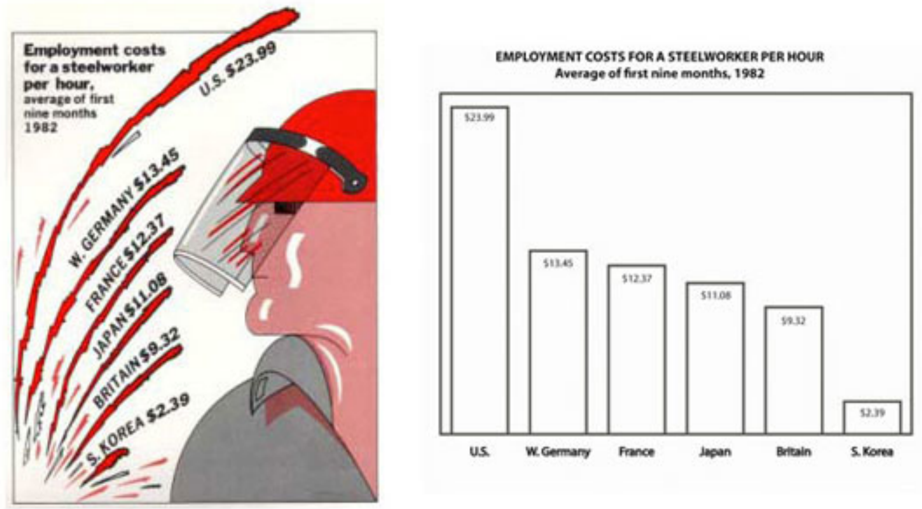

Figure 2.3. Example of embellished vs. plain chart with same data, from Bateman et al.

Another theoretical framework for statistical graphics that has already had huge influence is Ben Fry's Computational Information Design [Fry04], which presents a framework that attempts to link fields such as computer science, data mining, statistics, graphic design, and information visualisation into a single integrated practice. He argues a 7-step process for collecting, managing and understanding data: 1. acquire, 2. parse, 3. filter, 4. mine, 5. represent, 6. refine, 7. interact. Crucial to this framework is software that can simplify the implementation of each operation, so that a single practitioner can practically undertake all of these steps, allowing the possibility of design iteration to incorporate many of the stages, and facilitating user interaction through dynamic alterations of the representation. Fig. 2.4 represents the non-linear processing chain of Ben Fry in Computational Information Design.

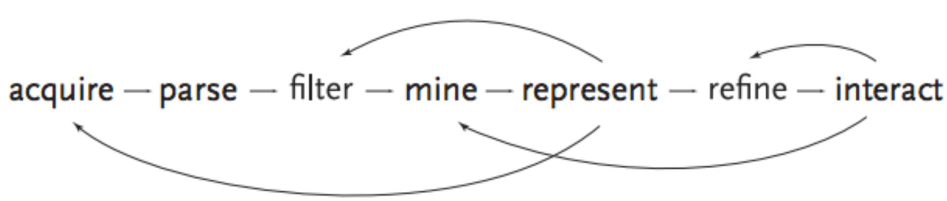

Figure 2.4.Computational Design Process, source: [Fry04]

2.2.1. DATA VISUALIZATION TECHNIQUES

Scientific data analysis is the process of refining potentially large amounts of measured or modelled data into a few simple rules or parameters which characterise the phenomenon under study. This may include quantifying known analytical relations between data parameters and inferring previously unknown relations. Visualisation and images are a by-product of this process not the result.

In 'Beautiful Evidence' Tufte describes principles of analytical graphics such as: showing comparisons, causality, mechanism, systematic structure, multivariate data, Integration of evidence, describing and documenting the evidence with labels, scales, sources, and finally the content.

Visualisation is used to understand data properties, finding patterns in data, suggesting modelling strategies, and to communicate results. The visualisation process usually starts with raw data which is transformed using data mining and/or signal/image processing techniques to extract patterns from it. The abstract data values get mapped into visual geometric primitives that are rendered and displayed.

According to Cleveland [Cle94], for summarising and displaying one-dimensional datasets, histograms, box plots and pie charts are mostly used. Pie charts for example, can only display one dimension, which is mapped to the size of a slice of a circular graph. Displaying relationships between two variables are usually represented by scatter plots or graphs. Even though scatter plots are typically two-dimensional, three-dimensional scatter plots exist as well.

Specifically for multi-variate datasets, the visualisation by Chernoff faces, Andrew curves, parallel coordinate curves or multivariate glyphs is used [TSS86]. These techniques can be combined in many ways or certain visualisations could be used for specific tasks. The most common technique for graphing data is a 2d scatter plot which is also used as a visual representation techniques for: Principal Component Visualisation (PCA) , Projection Pursuit (PP), Self-Organizing Maps (SOM), Multidimensional Scaling (MDS).

2.2.2. AUDITORY VERSUS VISUAL REPRESENTATION OF DATA

Auditory and visual representation of data both have their benefits and drawbacks depending on the application they are used for. Additionally information perceived from one of these two modalities can influence the performance on perception in the other one. In order to get a better understanding of sonification, it is necessary to explain where auditory representation of data is advantageous and where visual representation works better. In order to achieve these goals we need to understand how different our visual and auditory perception are.

The science that concerns itself with human auditory perception is known as psychoacoustics, and an understanding of the human auditory system is crucial in the use and optimisation of auditory displays.

According to Kramer et al. [KWB+99] here are some potential applications where auditory display is more advantageous:

- Monitoring tasks where eyes are busy and an eye free interface is useful to have; e.g. cockpit operations, network monitoring, and factory floors.
- Monitoring in high stress environments. Hennemann et al. presented that response time to an auditory signal can be shorter than a visual one [HL54] which is very useful in stressful situations where an immediate reaction is essential.
- Orienting tasks where ears tell eyes where to look [PSBS90]. This type of application is very useful when sound indicates the importance of a variable, and then the details of that variable may be delivered visually.
- Monitoring or analysing large data sets. Auditory system allows the ability of backgrounding; which is to listen to some sounds with a low attentional priority while giving enough awareness to those with higher priority.
- Comparing multiple data sets and monitoring multiple tasks is possible because of the capability of parallel listening.[GSO91]
- Exploring time-sequenced data with a wide dynamic range using auditory displays is possible because of the acute temporal resolution in the hearing sense. (dynamic range between milliseconds to several thousand milliseconds)

- Discovering overall trends in data is possible because of auditory gestalt formation. [Breg94] We may discern the sound as a whole without guiding our attention to its components. Auditory gestalt allows us to collect meaningful events in a stream of data.
- Our auditory sense is sensitive to temporal changes which is very useful in analysis of periodic/aperiodic events and temporal processes. [WD80]
- Remembering highly salient sonic patterns could be helpful in pattern recognition in data. [KWB+99]

Some potentials of visual modality over auditory one are:

- Visualization is culturally more pronounced. Ability to read visualizations has become common knowledge in western cultures. [Bie47]
- It can be created and played back without technical means. E.g. it's possible to draw a chart on a piece of paper quickly and discuss it whereas sound and auditory representations require at least devices for creation and playback.
- Possibility to save a discrete state of the data e.g. through taking screenshot of an animated graph at a specific time.
- The possibility to close the eyes or looking away gives the chance to take a break from the data representation whereas the ears are not made to be shot down at any time.

In addition to these individual characteristics of each sensory, how one influences the other has been studied by psychologists and neuroscientists. These studies have explored how information from different sensory modalities are selected and bound together in the brain to represent objects and events at several stages of perceptual processing. Most recent studies have revealed that auditory and visual modalities are closely related and mutually interplaying. E.g. in the domain of motion perception, Soto-Faraco et al. [SSK04] suggest that visual information influences auditory motion perception and there are common neural substrates to motion perception between the visual and auditory modalities.

Kim et al. [KPS11] reported the effect of auditory information on visual motion perception. They focus on spatial characteristic or motion of auditory stimuli. For example, auditory effects on visual motion perception manipulating the temporal relationship between a transient auditory stimulus and visual event.

In contrary, auditory effects on visual motion perception were reported to be absent or of a smaller size. E.g. Welch and Warren [WD80] stated that in spatial tasks where visual perception is more dominant, one will always depend on vision over audition to solve spatial problems. Thus, auditory stimuli can not at all influence one's perception of the location of a visual stimulus. However, recent studies have established results that contradict this hypothesis and concluding that it is the
precision of different sensory inputs that determines their influence on the overall perception. Changes in the location of sound can trigger visual motion perception of a static stimulus in far peripheral vision. E.g. a blinking visual stimulus with a fixed location was perceived to be in a lateral motion when it's onset was synchronized to a sound with an alternating left-right source or when it was accompanied with a virtual stereo noise source smoothly shifting in a horizontal plane.

Alais and Burr [AD04], suggest that the role of auditory spatial signals in cross-modal localization depends on the spatial reliability of the visual signal. Moreover, Perrot et al. [PSBS90] reported that location discrimination performance at angles of 20° or larger are better for the auditory modality than for the visual. Therefore, auditory spatial information can modulate visual motion perception when moving visual stimuli are presented in peripheral visual field.

The auditory and visual modalities have different ecological purposes, and respond in different ways [LMV99]. The fundamental difference is physiological though – human eyes are designed to face forward, and although there is a broad angular range of visibility, the most sensitive part of the eye, only focuses on the central part of the visual scene [War00], while the ear is often omnidirectional and used to monitor parts of the environment that the eye is not looking at currently. Eye movements and head movements are essential to view any visual scene, and the ears often direct the eyes to the important stimulus, instead of acting as a parallel information gathering system.

2.2.3. SONIFICATION OF DATA

Kramer et al. defined sonification as *"the use of non-speech audio to convey information or perceptualize data." or "Sonification is the transformation of data into perceived relations in acoustic signals for the purposes of facilitating communication or interpretation."* [KWB+99]

This definition focuses on two specific points; one is that the sound that conveys information is acoustic signal and can not be speech, second is that the output is information or perceptualized data and not raw data. The term 'perceptualization' of scientific data is first used by Grinstein et al. [GS90] interchangeably with the modern definition of 'visualisation', but later used by Auditory Display community free of the sensory bias for auditory and visual display of data.

Later Hermann redefined sonification in more specific terms as a system that uses data as input and generates sound signals as output with these constraints:

- The sound has to reflect objective properties or relations of the data used as input.
- The transformation has to be systemic, meaning that there has to be a precise definition of how the sound is influenced by the data.
- The sonification should be able to create sound that is always structurally identical with previous outputs, given the same data and identical iterations.
- the system has to have the possibility to be used with either the same data or with different data. [He08]

The latter definition pays special attention to the problem of reproducible and pervasive computing in sonification. Furthermore, it emphasizes on establishing standards by creating identical structures where the data to be sonified is similar. This allows a more systematic and formal comparison of sonification systems.

2.2.3.1. TYPES AND TECHNIQUES OF SONIFICATION

Sonification can be classified depending on:

- distributing technology (public/private , interactive/non-interactive, etc.)
- intended audience/users (data scientists, visually impaired, students, etc.)
- data source (world wide web, sensors, EEG, etc.)
- data type (analog, digital, spatial, temporal, etc.)

Besides these classifications, sonification can also be categorized into five techniques in terms of how sound is generated from data. [He02]

- Audification: is the direct conversion of data points into sound samples. In order to make the signal audible, it's usually scales into a hearable frequency range. E.g. Dombois used audification to perceptualize planetary seismic data [Dom01].
- Earcons: are abstract synthetic tones that can be used in structured combinations to create auditory messages [Brew94].
- Auditory Icons: are everyday non-speech sounds that directly represent the event that is being sonified. E.g. the sound of a paper basket being emptied represents metaphorically emptying trash in operating systems. Auditory icons are not as abstract as earcons. Bill Gaver introduced them by adding sounds to visual user interfaces in 1980s [Gav94].
- Parameter mapping sonification: is the mapping of the data values to specific attributes of sounds such as volume, pitch, panning, timbre or indirectly a combination of these attributes.
- Model based sonification: provides a setup of a dynamic system which is parameterized from the dataset. The model provides the dynamics that determine the elements' behaviour in time. Furthermore, some interaction modes are specified so that the user of a sonification model is able to interact with the model. The sonification is the reaction of the data-driven model to the actions of the user [He02].

Successful applications of sonification in exploratory data analysis must be paired with a systematic procedure of the working environment in which this analysis is conducted, along with the psychoacoustic principles that affect auditory perception. We discuss some examples of such sonification systems to explore their strengths and shortcomings.
The following data sonification tools all have a GUI (Graphical User Interface) and require no programming skills for the data analyst. The data is imported over text or Excel/CSV files, database support doesn't exist in these tools.

- Sonification Sandbox: is developed by Sonification Lab at Georgia Tech. [Wa03]. It creates auditory graphs using parameter mapping sonification and MIDI output for sound generation. Sonification Sandbox is used for experimenting with various sonification techniques, data analysis, science education, auditory display for blind, and musical interpretation of data. [Flo05] The latest version is available for all platforms.

- xSonify: is created by NASA and focused on sonification of space physics data such as Crossing the bow shock of Saturn; and detecting micrometeoroids impacting Voyager 2 when traversing Saturn's rings (these impacts were obscured in the plotted data but were clearly evident as hailstorm sounds) The main user group for this tool are visually impaired scientists and students [CSD06]. xSonify uses Java sound API and MIDI output.
- SonifYer: is developed by sonification research group at Berne University of the Arts [SD09]. It is mainly used for time series data such as EEG data, seismological data, and fMRI. In SonifYer audification and FM-based parameter mapping sonification is used.
- SoniPy: is based on Python programming language and hosted on sourceforge. It is designed to be a framework for data sonification using components of python for data acquisition, storage, and analysis and adding perceptual mappings and sound synthesis modules into it [WBBD07].

In recent years with growth of world wide web and other real time applications, the need for real-time monitoring of multiple data dimensions, such as for monitoring multiple sources of data has evolved. Some examples are financial data sonification systems [JC04] and [Wo09], twitter data sonification[DHW11] and [HNE+12], EEG [HBSR06] and sonification of astrophysics data [AOR+14], to name a few.

2.3. RESEARCH CHALLENGES AND OPEN QUESTIONS

There are numerous existing sonification tools with reference to theories of auditory perception and psychophysics but, to date, few have been adopted by a specific target user base through analysis of the environment, the nature of the data and the goals of the application . The assumption is that the core of this challenge is the fact that the auditory display methods have been designed and developed without involving the users throughout the design process. The result of such design is a tool that doesn't necessarily fulfil the user's needs, result in poorly designed displays, or stays at an experimental level.

In addition to functionality and usability, pleasure is also a central goal in designing products and applications. Users want something more than just usable: they want applications that offer something extra that they can relate to; products that bring not only functional benefits but also emotional ones. Designing aesthetically appealing interfaces is about understanding the users and respecting humans diversity. Finally, visualization is a mature and developed field in comparison to the younger field of sonification. Despite of this maturity, there are specific tasks in specific domains with specific data that could be more suitable to explore using auditory feedback.

Some of the open questions that are going to be tackled in the next chapters concerning Human-Computer-Interaction (HCI) are:

- What are some HCI methods suitable for designing auditory interfaces?

- How is a User-Centered-Design process adapted to design of sonification interfaces?

- Given a sonification framework, how to create a pool of sonifcations? Where do these techniques fail and where are they superior to visualisation?

- How to develop some standard sonification techniques which assist the data mining work-flow for data scientists?

Working on these questions, the purpose is also to touch the surface by some of the main sonification questions open in the auditory display and sonification community such as:

- Which tasks are best suited to the visual and auditory modalities?
- What kind of data sets might be better suited to visual or auditory display?
- How to identify the auditory dimension that best represents a data dimension?
- How to capture changes in data by a direction change in the auditory dimension?
- How to determine the scaling factor that should be used. (A question that has been raised by Walker et al. [WKL00] several times)

3 HCI DESIGN PROCESS

Why are so many user interfaces hard to use? Why are user interfaces difficult to design and implement? What is HCI and Usability Engineering Process, and how can it help improve user interfaces? Why should we be trained in user interface design? This chapter will provide a quick overview of the challenges and opportunities in HCI fundamentals, user interface design and implementation. It will include a subset of HCI design principles used for designing and evaluating in this report.

Human-Computer Interaction (HCI) is defined by the Association for Computing Machinery (ACM) Special Interest Group on Computer-Human Interaction (SIGCHI) as *a discipline concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of the major phenomena surrounding them.* HCI is a multidisciplinary field, which combines theories and practices from various fields including computer science, cognitive science, psychology, sociology, and more. According to John Carroll [Car02], *HCI is about understanding and creating software and other technology that people will want to use, will be able to use, and will find effective when used.*

Wania et al. [WAM06] categorised the communities in HCI research into seven clusters: Design Theory and Complexity, Design Rationale, Cognitive Theories and Models, Cognitive Engineering, Computer-Supported Cooperative Work (CSCW), Participatory Design, and User-Centered Design.

HCI studies the interactions and the relationships between humans and computers. HCI is more than user interfaces and more than ``screen-deep'' (Computer Science and Technology Board of National Research Council, 1997); it is a multidisciplinary field covering many areas [HLP97]. In the first ten to fifteen years of its history, HCI has focused on interfaces (particularly on the possibilities
and design criteria for graphical user interfaces (GUIs) using windows, icons,menus, and pointing devices (WIMPs)) to create more usable systems. As interface problems were better understood, the primary HCI concerns started to shift beyond the interface (to respond to observations

as articulated by D. Engelbart: *If ease of use was the only valid criterion, people would stick to tricycles and never try bicycles*).

More recent HCI research objectives [Fis93] are concerned with tasks, with shared understanding, and with explanations, justifications, and argumentation about actions, and not just with interfaces. The new essential challenges are improving the way people use computers to work, think, communicate, learn, critique, explain, argue, debate, observe, decide, calculate, simulate, and design.

Some of the beginnings of user modelling were derived from the need and desire to provide better support for human-computer collaboration. Collaboration in this context is defined as ***a process in which two or more agents work together to achieve shared goals*** (Terveen, 1995). Some fundamental issues (such as shared goals, shared context, control, (co)-adaptation, (co)-evolution, and learning) can be derived from this definition. Human-computer collaboration can be approached from two different perspectives:

- The ***emulation approach*** is based on the metaphor that to improve human-computer collaboration is to endow computers with ``human-like abilities''.

- The ***complementing approach*** is based on the fact that computers are not human and that human-centred design should exploit the asymmetry of human and computer by developing new interaction and collaboration possibilities (Suchman, 1987).

Historically, the major emphasis in user modelling has focused on the human emulation approach. However, based on the limited success of the emulating approach, the interest has shifted more and more to the complementing approach (Bobrow, 1991). There is growing evidence that the problems of user modelling in the complementing approach are more tractable, more feasible, and more desirable, as evidenced by their increasing influence in the design of commercial high-functionality applications (Horvitz et al.,1998).

The original HCI approaches, by being focused on making systems more usable, have often reduced the expressive power of the systems and of interfaces to accommodate novices and casual users who are assumed to be using the system for the first time, for only a few times, and for simple activities. Walk-up-and-use systems, such as ATMs (Automated Teller Machines), are examples of low-threshold, low-ceiling systems; they should be easy to understand and use without prior experience. Complex systems for professional use need to be useful; they must allow their users to do the tasks they have to do to get their jobs done.

These professional worlds are complex, leading to high-functionality applications (HFA). These systems are often difficult to use at first, but over time users are able to perform a wide range of tasks with the system. Generic assumptions about users may be adequate in systems for novices (the design criteria being based on generic cognitive functions, as, for example, de¢ned by the Model Human Processor (Card et al., 1983)), but only if we ignore the requirements to provide universal access for people with different (dis)abilities (Stephanidis, 2001). Generic assumptions about skilled domain workers being the primary users of HFAs are definitely limiting the learnability and usability of these systems.

3.1. KNOWLEDGE BASED HCI

Traditionally, computer usage was modelled as a human-computer dyad in which the two were connected by a narrow explicit communication channel, such as text-based terminals in a time-sharing environment. The advent of more sophisticated interface techniques, such as windows, menus, pointing devices, color, sound, and touch-screens have widened this explicit communication channel. In addition to exploring the possibilities of new design possibilities for the explicit communication channel, knowledge-based architectures for HCI have explored the possibility of an implicit communication channel.

The implicit communication channel supports communication processes that require the computer to be provided with a considerable body of knowledge about problem domains, about communication processes, and about the agents involved.

- Knowledge about the problem domain: Shared knowledge builds upon large amounts of knowledge about specific domains. This knowledge constrains the number of possible actions and describes reasonable goals and operations in the domain of specific users, thereby supporting human problem-domain interaction and not just human-computer interaction (Fischer, 1994; Horvitz et al., 1998).

- Knowledge about communication processes: The information structures that control communication should be accessible and changeable by the user. A knowledge-based HCI system should have knowledge about when and whether to assist the user, interrupt the user, and volunteer information to the user contextualized to the task at hand (Fischer and Stevens, 1987; Horvitz, 1999).

- Knowledge about the communication agent: The ``typical'' user of a system does not exist; there are many different kinds of users, and the requirements of an individual user usually change with experience (Mackay, 1991). Simple classification schemes based on stereotypes (Rich, 1989), such as novice, intermediate, or expert users, are inadequate for complex knowledge-based systems because these attributes become dependent on a particular context rather than applying to users globally. One of the central objectives of user modelling in HCI is to address the problem that systems will be unable to interact with users cooperatively unless they have some means of finding out what the user really knows and does. Techniques to achieve this include: (1) being told by the users (e.g. by questionnaires, setting preferences, or specification components (Nakakoji, 1993)); (2) being able to infer it from the user's actions (e.g. by using critics (Fischer et al., 1991; Mastaglio, 1990)) or usage data (Adachi, 1998; Hill et al., 1992); and (3) communicating information about external events to the system (Bolt, 1984; Harper et al., 1992).

3.2. DESIGN TIME AND USE TIME

One of the fundamental problems of system design is: how do we write software for millions of users (at design time), while making it work as if it were designed for each individual user (who is known only at use time)? Figure 3.1 differentiates between two stages in the design and use of a system. At design time, developers create systems, and they have to make decisions for users for situational contexts and for tasks that they can only anticipate. For print media, a fixed context is decided at design time whereas for computational media, the behavior of a system at use time can take advantage of contextual factors (such as the background knowledge of a user, the specific goals and objectives of a user, the work context, etc.) only known at use time. The fundamental difference is that computational media have interpretive power: they can analyse the artefacts created by users and the interaction patterns between users and system, and they can support users in their articulation of additional contextual factors.

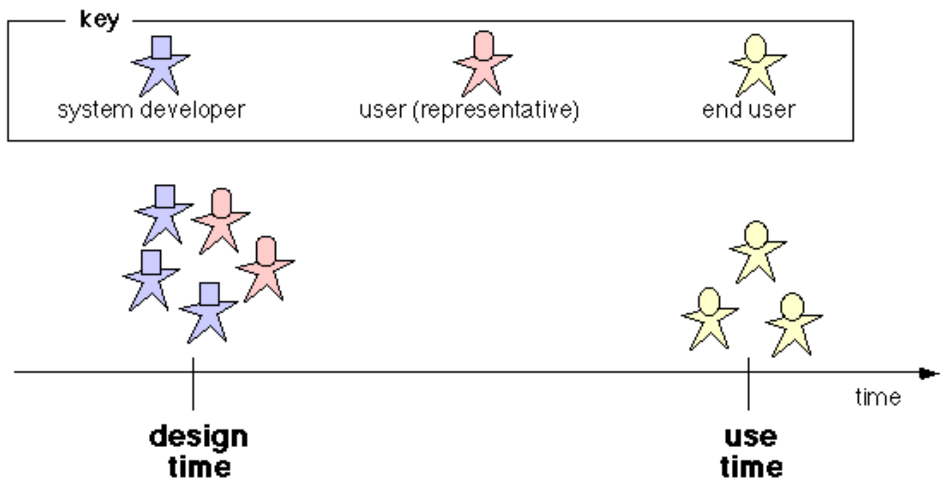

Figure 3.1. Design and Use Time

An important point about user modelling might be that use time and design time get blurred. If the system is constantly adapting or is being adapted to users, use time becomes a different kind of design time (Henderson and Kyng, 1991).

The need to support a broad class of different users leads to high-functionality applications with all their associated possibilities and problems. A feasible design strategy to support users in their own domain of knowledge is that system designers make assumptions about classes of users and sets of tasks in which they want to engage - a design methodology leading to domain-oriented systems (Fischer, 1994).

3.3. DESIGN PRINCIPLES AND METHODOLOGIES

HCI design process is:

- A goal-directed problem solving activity informed by intended use, target domain, materials, cost, and feasibility

- A creative activity
- A decision-making activity to balance trade-offs (e.g., requirements of product compatibility and ease of use may be contradicting)

It is a representation:

- A plan for development
- A set of alternatives and successive elaborations

Four basic activities of interaction design:

1.Identifying needs and establishing requirements
- Who our target users are?
- What kind of support an interactive product can provide?

2. Developing alternative designs
- Suggest ideas for meeting the requirements
- Conceptual design: produce the conceptual model for the product, e.g., what the product should do, behave and look like
- Physical design: consider detail of the product including the colors, sounds, images to use, menu design, icon design, etc.

3. Building interactive versions of the designs

- Not necessarily build a software version, other possible simple prototypes include paper-based storyboard, wood, etc. e.g., When the idea for the PalmPilot was being developed, Jeff Hawkin carved up a piece of wood about the size and shape of the device he had imagined. He used to carry this piece of wood around with him and pretend to enter information into it, just to see what it would be like to own such a device

4. Evaluating designs
- Determine usability & acceptability of product or design
- Require user involvement throughout development

Users are the people who are going to use a final system to accomplish a certain task or goal. Kuniavsky defines user experience as the totality of end users' perceptions as they interact with a product or service. These perceptions include effectiveness (how good is the result?), efficiency (how fast or cheap is it?), emotional satisfaction (how good does it feel?), and the quality of the relationship with the entity that created the product or service (what expectations does it create for subsequent interactions?) [Kun10]

3.3.1. USER CENTERED DESIGN

Before understanding what User Centered Design (UCD) is, we have to define who the users are.

Most obvious definition is that the user is who interacts directly with the product or system to achieve a task or goal.

A wider definition of user is:

- Primary: The person who uses the design directly

- Secondary: The person who either supplies input or receives output from the design

- Tertiary: Those affected by the introduction of the system or who will influence its purchase

Another user definition is stakeholder:

- People or organizations who will be affected by the system and who have a direct or indirect influence on the system requirements

- A broad user definition, e.g., direct users and their managers, people who may lose their job because of the introduction of the new product, etc.

What is meant by user needs is not simple to ask them what do you need? because people do not necessarily know what is possible. We rather need to understand:

- Characteristics and capabilities of users

- What they are trying to achieve

- How they achieve it currently

- Whether they would achieve their goals more effectively if they were supported differently

- e.g., in designing a child's toy – a toy should not require too much strength to operate, but may require greater strength to change battery

- For new invention, the "future" needs can be indicated from similar behaviour that is already established

    - e.g., need identification of cell phones can be started from investigating behaviour in standard telephones: call making, phone book services, voice mail services, the number of the last person to ring, etc.

    - e.g., e-commerce developers have found that referring back to customers' non-electronic habits and behaviours can be a good basis for enhancing e-commerce activity

Three principles for user-centred approach

1. Early focus on users and tasks

- First understand the users by studying their cognitive, behavioural and attitudinal characteristics
- Require observing users doing their normal tasks, studying the nature of those tasks, and then involving users in the design process
- Can be expanded and clarified further:

    - Users' tasks and goals are the driving force behind the development
    - Users' behaviour and context of use are studied and the system is designed to support them
    - Users' characteristics are captured and designed for
    - All design decisions are taken within the context of the users, their work, and their environment

- Users are consulted throughout development from earliest phases to the latest and their input is seriously taken into account

2. Empirical Measurement

- Users' reactions & performance to manuals, simulations, prototypes, etc. are observed, recorded & analysed

- Identify, document and agree specific usability and user experience goals at the beginning of the project

- Help designers to choose between different alternative designs & to check on progress as the product is developed

3. Iterative Design

- When problems are found in user testing, fix them and carry out more tests

3.3.2. LIFE CYCLE MODELS

Life cycle models show how activities are related to each other.
They are management tools or simplified versions of reality.
Many lifecycle models exist, e.g., waterfall model for software engineering, Star model for HCI and and ISO 13407. Figure 3.2. shows a simple HCI life cycle model that ends with evaluation to ensures the final product meets the prescribed usability criteria.

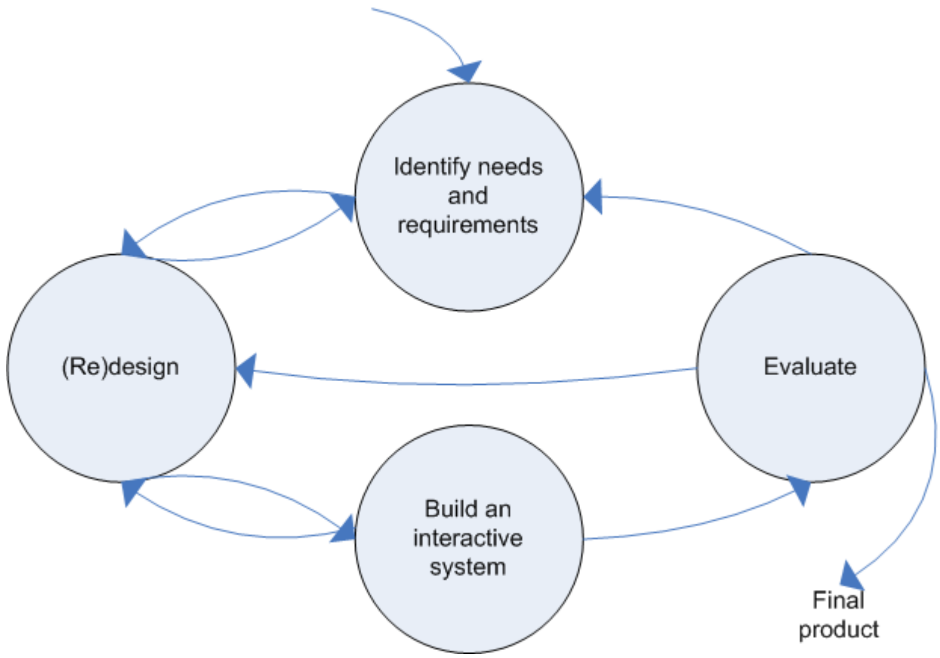

Figure 3.2. HCI life cycle model

Another common HCI life cycle model is Star lifecycle suggested by Hartson and Hix (1989). (shown in Figure 3.3)

Important features of Star lifecycle are:

- Evaluation is at the center of activities
- Interconnected via the evaluation activity
- No particular ordering of activities. Development may start in any one of the activities
- Derived from empirical studies of interface designers

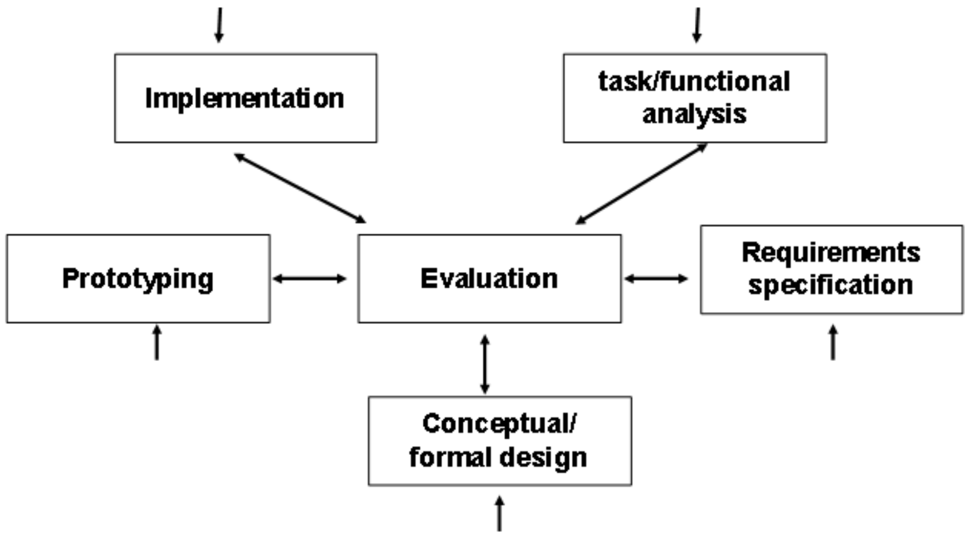

Figure 3.3. Start life cycle model

n order to explore paradigms and principles concentrated on examining the product of interactive system design we could also learn from software development. Software engineering is the emerging discipline for understanding the design process, or life cycle. Designing for usability occurs at all stages of the life cycle, not as a single isolated activity. The activities in a simple waterfall lifecycle model is illustrated in the Figure 3.4. but a more detailed set of activities are explained in the next pages.

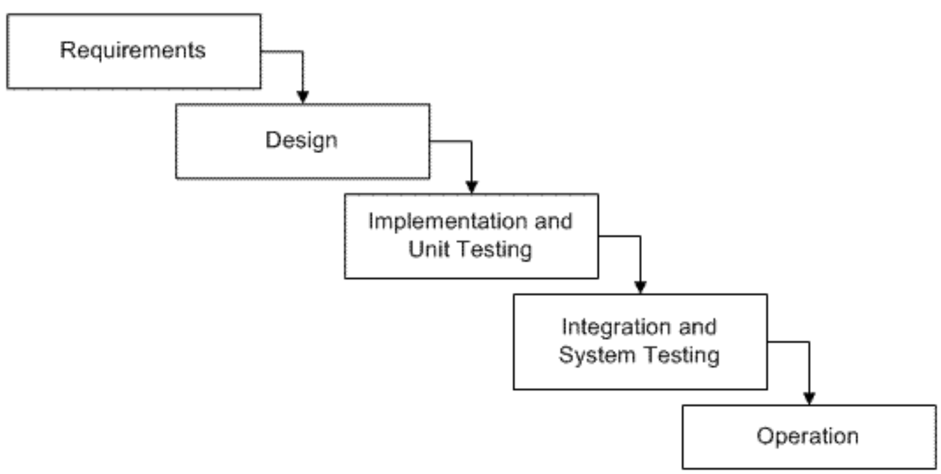

Figure 3.4. Waterfall lifecycle model of software development.

Requirements specification

- designer and customer try capture what the system is expected to provide

- can be expressed in natural language or more precise languages, such as a task analysis would provide

Architectural design

- high-level description of how the system will provide the services required

- factor system into major components of the system and how they are interrelated

- needs to satisfy both functional and nonfunctional requirements

Detailed design

- refinement of architectural components and interrelations to identify modules to be implemented separately

- the refinement is governed by the nonfunctional requirements

Coding and unit testing

- implementing and testing the individual modules in some executable programming language

Integration and testing

- combining modules to produce components from the architectural description

Operation and maintenance

- product is delivered to customer and any problems/enhancements are provided by designer while product is still live

- the largest share of the life cycle

The lifecycle of interactive systems is more iterative and we cannot assume a simple linear sequence of activities as assumed by the waterfall model. Figure 3.5. illustrates the lifecycle for interactive systems.

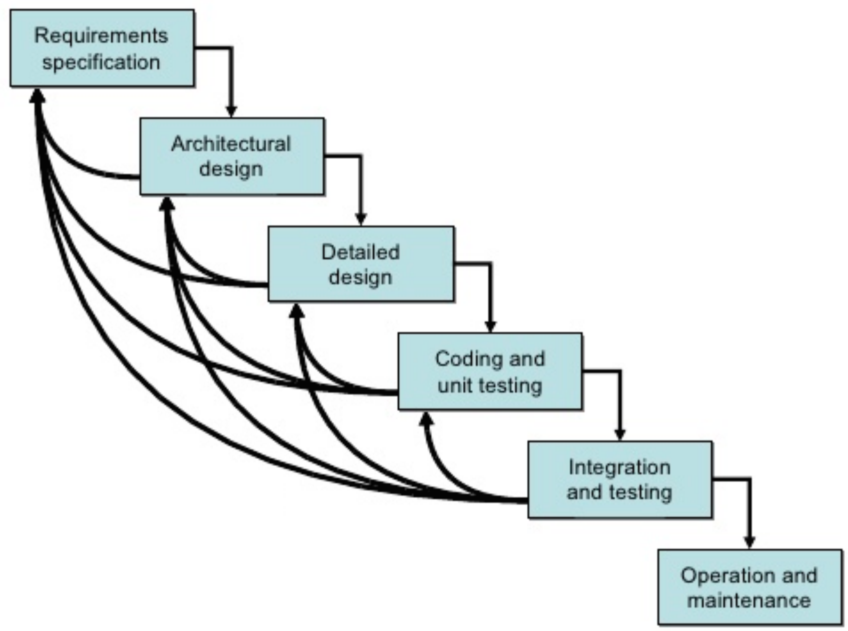

Figure 3.5.The lifecycle for interactive systems.

3.1.3. STANDARDS AND GUIDELINES

Design rules suggest how to increase usability. Some of the questions we need to answer with usability are :efficiency (how fast or cheap is it?), emotional satisfaction (how good does it feel?), and the quality of the relationship with the entity that created the product or service (what expectations does it create for subsequent interactions?) [Kun10]

- Standards are set by national or international bodies to ensure compliance by a large community of designers, standards require sound underlying theory and slowly changing technology, hardware standards more common than software, high authority and low level of detail, and ISO 9241 defines usability as effectiveness, efficiency and satisfaction with which users accomplish tasks.

Usability engineering is the ultimate test of usability based on measurement of user experience. Usability engineering demands that specific usability measures be made explicit as requirements. Usability includes:

- Usability attribute/principle
- Measuring concept
- Measuring method
- Now level/ worst case/ planned level/ best case

Some common problems with usability are that:

- Usability specification requires level of detail that may not be possible early in design
- Satisfying a usability specification does not necessarily satisfy usability

Iterative design overcomes inherent problems of incomplete requirements. Prototypes simulate or animate some features of intended system. There are three different types of prototypes:

- Throw-away
- Incremental
- evolutionary

4 REQUIREMENT ANALYSIS: PRE DESIGN

4.1. USER CENTERED DESIGN APPROACH

Users are the people who are going to use a final system to accomplish a certain task or goal. Kuniavsky defines user experience as the totality of end users' perceptions as they interact with a product or service. These perceptions include effectiveness (how good is the result?), efficiency (how fast or cheap is it?), emotional satisfaction (how good does it feel?), and the quality of the relationship with the entity that created the product or service (what expectations does it create for subsequent interactions?) [Kun10]

User Centred Design (UCD) means that the designed systems are balanced between user goals, designer's objectives, and technological capabilities. It involves user feedback and research throughout the entire design and implementation process. In UCD the goal is to determine how users work, how they think, and how they live. In UCD end users influence how a design takes shape. Design methodologies, such as UCD and participatory design, incorporate the user in the design process. In both of these methods users provide feedback during the design phase and allow designers and developers to iteratively refine the designs. Nevertheless, when these designs are finalised and employed, modifications are not supported. Therefore, we go beyond user-centeredness and explore meta-design in this process. Designing interactive software systems without enough knowledge about the users could leave them frustrated and unable to complete a task while using the system. Cross and Norman relate to design as more than a problem solving activity. Cross[Cro82] described designerly ways of knowing, doing and acting with user empathy at its core. Empathy has been invoked as a core value to UCD [Nor86] as well. Patnaik and Becker [PB99] emphasise the power of affinity and outline the steps that help identify development opportunities including to let users guide the flow of research, collecting data in a variety of different forms, and integrating research and design in series of iterative stages as a way to tweak results. Problem solving has often been a part of the extended definition for design actions but it is often only part of a larger context. Gasson [Gas03] enumerated design as 1) problem setting, 2) problem solving, 3) situated learning and 4) functional analysis. Some also commented that design cannot be comprehended as problem solving [Sto92]; or is a richer concept than problem solving [WBDH95].

UCD is an extensive term to describe how users form and influence the design processes. Norman introduced it in 1980s and made it widely used by the publication of the book; User-Centred System Design: New perspectives on Human Computer Interaction [Nor86]. UCD encompasses a huge variety of methods in which users are involved one way or another. Sometimes users are only involved sparsely at specific time during the design process; typically during requirement gathering and usability testing, and sometimes they have impact by being involved intensively throughout the design and implementation working with designers and developers. Norman expanded UCD concept further in his book "The Design Of Everyday Things" [Nor02] His four main suggestions on how design should work are:

- Make it easy to determine what actions are possible at any moment.
- Make things visible, including the conceptual model of the system, the alternative actions, and the results of actions.
- Make it easy to evaluate the current state of the system.
- Follow natural mappings between intentions and the required actions; between actions and the resulting effect; and between the information that is visible and the interpretation of the system state.

In these suggestions the user is at the centre of the design process. The designer should make the task easy to understand for the user and make sure that the user is able to use the system/product the way it is intended to be used within a minimum effort to learn. Furthermore, Norman suggests accompanying products by a fact sheet that can be read very quickly and utilises the user's knowledge.

Norman emphasised to fully explore the needs of the users in terms of the use of the system and to involve the users in their actual environment in which they would use the designed system naturally. Preece et al. confirmed that the involvement of the users lead to more effective, efficient, and safer products and contributed to the acceptance and success of the products [RSP11].

In late 80s Ben Shneiderman articulated a similar guideline in the form of eight golden rules [Sch92]. He proposed a collection of principles that are derived heuristically from experience and application in most interactive systems. Some of his golden rules that are relevant in this thesis are: striving for consistency, offering informative feedback to the users, simple error handling, easy reverse of actions, reducing the use of short term memory, and learnability of the system. A decade later Jakob Nielsen adapted similar concepts to produce heuristics for usability engineering [Nie94a]. Some of the main heuristics of Nielsen are: visibility of system status, recognition/not recall, and helpful error messages.

The major advantage of the UCD approach is that it gives the designers a deeper understanding of the users at every stage of the design and evaluation of the product. The involvement of the users assures that the product is suitable for its intended purpose in the environment in which it is supposed to be used. It also leads designers to manage user's expectations about a new product. When users have been involved from the early stages of the design, they know what to expect and they feel that their thoughts and suggestions have been taken into account throughout the process. This causes a sense of ownership that guides to a higher fulfilment and smoother integration of the product into the user's environment [9]. The main disadvantage of UCD is that it can be costly and time consuming. It takes time to gather data from and about users and their environments. The process requires financial and human recourses. The other challenge is that the UCD teams are usually very multidisciplinary to better understand user's needs and communicate it to the technical developers in team. The disadvantage of this approach is that members of the team need to learn to communicate effectively with each other and with the users. This process can also be very time consuming.

UCD could be extended to meta-design [GF08] to shift some control from designers to the users by empowering them to create and contribute their own objectives in the design process. A system is a living entity, which evolves during and after the design process continuously. Thus, the participation of the users in the design decisions go beyond the processes at the design time. Participatory design [MK93] also involve users in the co-design process with the designers but despite the advantages of participatory design during the design time, systems need to be evolvable to fit new needs and tasks created by users after the completion of the system. Therefore, in order to have the users fully involved to contribute and modify the system themselves when new needs arise a combination of UCD, participatory, and meta-design would be satisfactory.

4.2. USER CENTERED DESIGN FOR AUDITORY DISPLAY

The history of sound in Interface Design is beyond the scope of this thesis but outlining Auditory Interface Design and Development is necessary to get a deeper understanding of the core concepts.

Frauenberger describes in his thesis [FS09] the history of sound in technology and the use of it in the very first personal computers. He indicates the gaming industry as the main incentive behind the development and improvement of sound in computers. Furthermore, he unveils the difference between "Auditory Display" and "Auditory (user) Interface". The former includes any use of auditory means to convey information, which is similar to definition of sonification by Kramer [KWB+10]- the use of non-speech audio to convey information - . It covers the auditory representation of data as well as the use of sound in user interfaces. "Auditory (user) Interface" is described as a sonic analogous to graphical user interface (GUI) and is mainly common to use for speech interfaces. Frauenberger states that the term "interface" implies a bidirectional communication, while "display" focuses on the presentation and feedback of information. Thus, an auditory user interface includes both channels of interaction.

Analysis of requirements and constraints, understanding the user’s in the context of the system's functionality and the tasks that she is involved with are the key constituents for a successful design process. The concept of Task and Data analysis (TaDa!) was first developed by Barrass [Bar96] as the first step for auditory information design. The “TaDa!” approach has three stages: The first one is a free-text scenario and five classification attributes (generic questions, purpose, mode, type, and style). The second step takes the information from the first one and derives questions of the task analysis. The third step focuses on the data. “TaDa!” includes some key aspects of requirement analysis in general, but it ignores limitations concerning the environment and the display the system is going to be implemented on. Additionally Barrass explored reinvention of design [Bar03] by introducing design patterns into the sonification field. Design patterns are first introduced in the field of Architecture by Alexander [FS09] and then got expanded into many other disciplines. Here’s the definition of pattern language by Alexander:

"... The elements of this language are entities called patterns. Each pattern describes a problem that occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice."
— Christopher Alexander

Frauenberger examined the concept of design patterns for auditory display design by analysing 23 proceedings of ICAD (International Community for Auditory Display) 2007 on four themes: design process, guidance, rationale, and evaluation. He describes that all papers introduce the application domain, but contextual information is not playing a role in the design process. After the in-depth view on design issues, he looks at the field of design in sonification from HCI community's point of view using an online survey. The results of this research show that the design process for auditory display is mostly unstructured and it provides limited support to reuse the design knowledge created. Another issue is that methodologies and existing guidance in audio domain are often tied to a specific context and reusing them is only possible within the restricted context [FTB05].

Besides design patterns, another design approach that has been expanded into auditory interface design is Ecological Interface Design (EID). EID presents guidelines for the development of displays where a key component is the mapping of real world properties to the interface. Furthermore, it is a design technique that originates from cognitive work analysis (CWA) which is a procedure to identify requirements for the interfaces of complex real time systems. EID uses some of the phases of CWA such as work domain analysis, control task analysis, and semantic mapping. *Work Domain Analysis* provides information about why the system exists, the flow of information through it and its functions. It helps to identify work domain characteristics and relations that are needed to be displayed in any interface. E.g. physical properties of work domain may specify if edification or parameter mapping sonification is suitable. At this point the information is not sufficient for interface design. *Control Task Analysis* provides information about what needs to be done, by whom, when, and how information about activity might be transmitted. It also gives information about temporal relations between tasks. E.g. it gives information about which tasks are better suited to be displayed visually and which tasks are more appropriate for auditory display. *Semantic*

Mapping provides information about criteria for choosing interface elements so that goal related task invariants are mapped into perceptual properties of the interface. E.g. it gives designers a framework to decide on dimensions of an auditory stimulus, based on knowledge of auditory perception.

EID differs from UCD in that the focus of the analysis is on the work domain rather than the end user or specific task. EID fundamentals are not limited to visual displays; however, it has been commonly utilised in visual display design. Gaver used ecological concepts in his work on auditory icons and earcons. This technique has also been used to the sonification of real time data [Gav93]. Gaver et al. [GSO91] used ecological approach in the Arkola simulation of a bottling plant and [Myn97] used it in a marine power plant but they did not use a full EID analysis. Instead they emphasised on how to represent physical functions acoustically. A full EID approach with higher order properties in auditory display design was first introduced by Sanderson et al. [SAW00] argued that if EID is to be used for designing auditory interfaces, in addition to the semantic mapping, an attentional mapping phase is needed. This phase provides requirements on how an auditory display should control attention alongside other interface elements, based on knowledge of auditory attention.

4.3. RESEARCH PROCESS AND DATA COLLECTION METHODS

Within a qualitative approach, several studies were suited for an applied ethnographic study design [DL09]. Ethnography is a methodology conceived to collect thick descriptions of human activity in real-world scenarios. In this case, it is the real world of climate scientists' activity in a research institution. By observing scientists in their natural work settings and team meetings, field notes were captured with regard to the context of self chosen data analysis tasks, a team meeting for each research team, and the interactions within the teams. In each study an observer and an interviewer visited actual users (climate scientists) in their workplace to capture, categorise, and analyse the users' activities, individual and team reflections, workflows, and the environmental factors throughout the tasks.

Qualitative research was chosen to better understand and situate complexity in a broader context [LLG11]. With activities of data scientists, the intent was to collect a holistic understanding over a reductionist understanding [Sch00]. The main objectives of this methodology are to gain meaning from scientists' experiences [BB98]. The purpose was not to engage quantitative research methods and seeking to test hypotheses. The qualitative research methods employed allow for gathering rich data needed to develop contextual and interpretive understanding.

Qualitative research methods were used to analyse an hour of individual data analysis work (contextual inquiry), an hour of observed team meeting (focus groups), and an hour of listening test to gather information on user's sound preferences. The listening test was conducted at a later stage of the studies and the participants were not all the same as the ones who participated in the first two studies. Data sources included:

- Observations, in a data analysis task
- Audio recordings
- Notes of the interviewer and observer during the studies
- Discussions within focus groups
- Discussion with the project partners in the climate science research institution during quarterly meetings.

Classification	Category	Number of Participants
Research Group	ReLoClim ArsCliSys EconClim	7 6 5
Gender	Male Female	10 8
Qualification	MS PhD PostDoc Professor Engineering Staff	1 8 6 1 2
Frequency of Data Analysis Tasks	Once/day Once/week Less often	58% 35% 7%

Table 1: Participants of the Contextual Inquiry

The first study consisted of a contextual inquiry and a focus group. Eighteen climate scientists (10 male, 8 female) from three different research groups participated in this study. The focus was the user goals of the scientists during their data analysis tasks. In addition to this needs assessment, the interdisciplinary nature of the project made it necessary to add a second evaluation method using focus groups on the language that climate scientists use in their research. In the later study the sound preference of 8 climate scientists and 8 sound experts was evaluated.

4.3.1. CONTEXTUAL INQUIRY

In a field study an observer and an interviewer visited actual users (climate scientists at Wegener Center for Climate and Global Change: https://wegcenter.uni-graz.at/) in their workplace to analyse their activities, workflows, and the environmental factors while analysing data. For the individual interviews, a questionnaire was prepared for the interviewer and observer, who assessed the general questions and marked if all relevant topics have been covered during the open task. A short introduction was given on the project. Then, the participant's personal background and qualifications were assessed. The central part of the individual interview session consisted of a walkthrough [Nie94b] of a self-chosen data analysis task, followed by the conditions that the participant had completed recently, s/he had been faced with raw data and wanted to understand it better to find out something about the data (successfully or not), s/he discussed with colleagues or presented at a meeting. The focus was on exploring the user goals of the scientists. Basic types of performance metrics were gathered from open questions such as:

- If it is mainly the task-success that users are interested in.
- How quickly can users perform a task and
- How efficient are they,
- how are errors found during the process (e.g., faulty data),
- how and when do participants reach proficiency in a programming environment, and
- how much time are they willing to invest in learning a new methodology.

Finally, expectations about an auditory display were collected, including a recording of what the data in the task would sound like, which data sets would be most useful for the participants to sonify, and their expectations towards how climate related phenomenon or progressions in climate data should sound like. Each of these interviews took about an hour.

4.3.1.1. ANALYSIS OF WORKFLOW AND SOFTWARE TOOLS

As quantitative information, we assessed the current use of software tools. Qualitative analysis was done on the workflows that the scientists follow, including typical tasks that have to be solved in the data analysis process. Furthermore, the visualizations that were involved in the tasks were categorized to get an overview of their strengths and weaknesses.

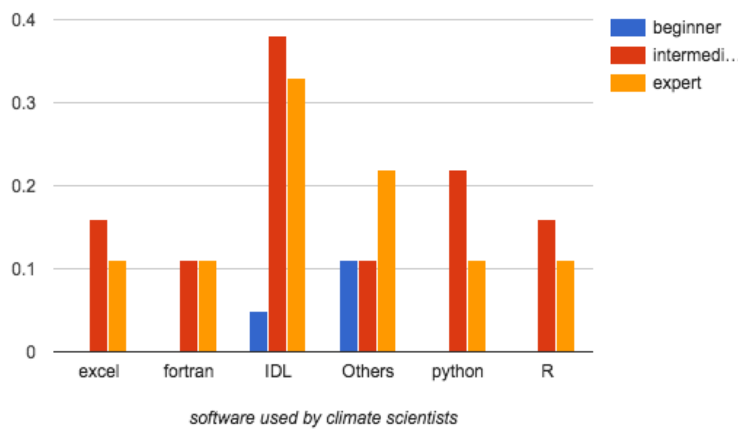

Figure 4.1. Software used by the climate scientists

For a further analysis, we assessed and analysed the visualisations that were used in the exemplary tasks during the interviews. We were surprised to find that the average number of data sets that the scientists wanted to compare with each other in one task was as high as 47, with single tasks demanding up to 400 sets (25 different colour-coded climate models, provided for four different altitudes of the atmosphere and for four different regions, i.e. each having 16 sequential plots.) About half of the visualisations are more or less self-explanatory, assuming a basic understanding of the field, but a few of them were either difficult to understand or, in the case of the 400 data slices, even confusing. The visualisation methods chosen mostly employed standard methodology, e.g. line charts and maps. A few researchers developed their own visualisations. Fig.4.2 shows typical visualisations in climate science.

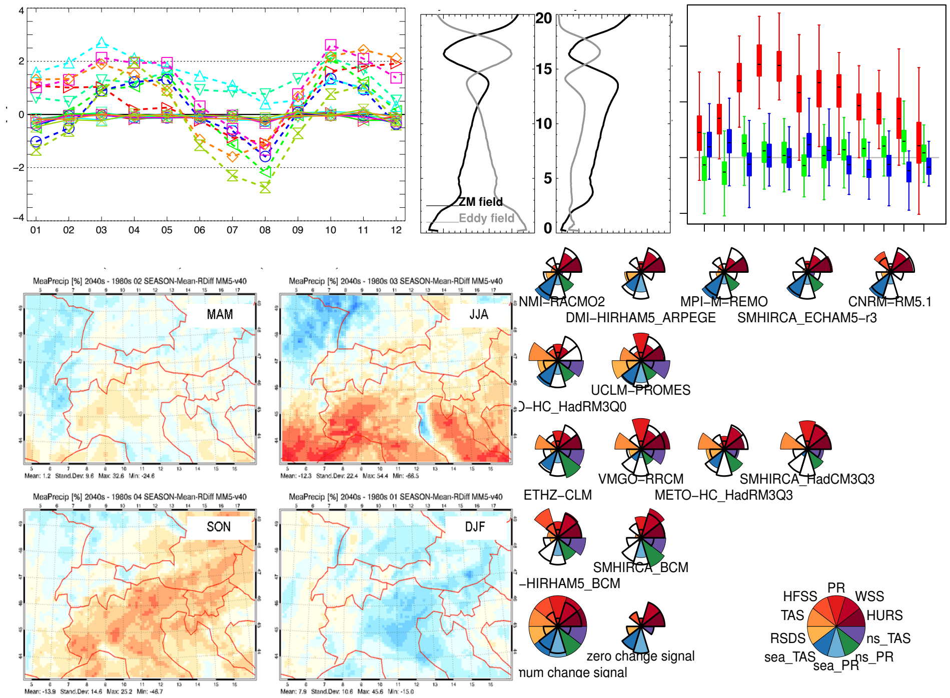

Figure 4.2. Some common visualization used by climate scientists. From left above to right below: 1) Line chart-time series, 2) Line chart- height orofile, 3) Bar chart with error bars, 4) Maps with descrete color coding, 5) Pie charts.

An overview of different software that the climate scientists use for data analysis and visualization is shown in Figure, including their own assessment of their expertise (beginner, intermediate,or expert). IDL, Interactive Data Language, is the most used software due to historic reasons at the institute. While IDL is a commercial program, open source languages such as Python and R are upcoming according to what the participants reported informally.

In general, it could be seen that all participants were very familiar with coding themselves rather than using ready-made software packages, and are used to scripting on the command line level. Another observation is that some basic applications have not been declared for this list by most participants, probably because they are such basic command-line tools, notably ncview, a netCDF visual browser (where netCDF is the typical data format for climate data). Ncview is a simple open source project for quick data visualization that most scientists use for a quick-check of their data.

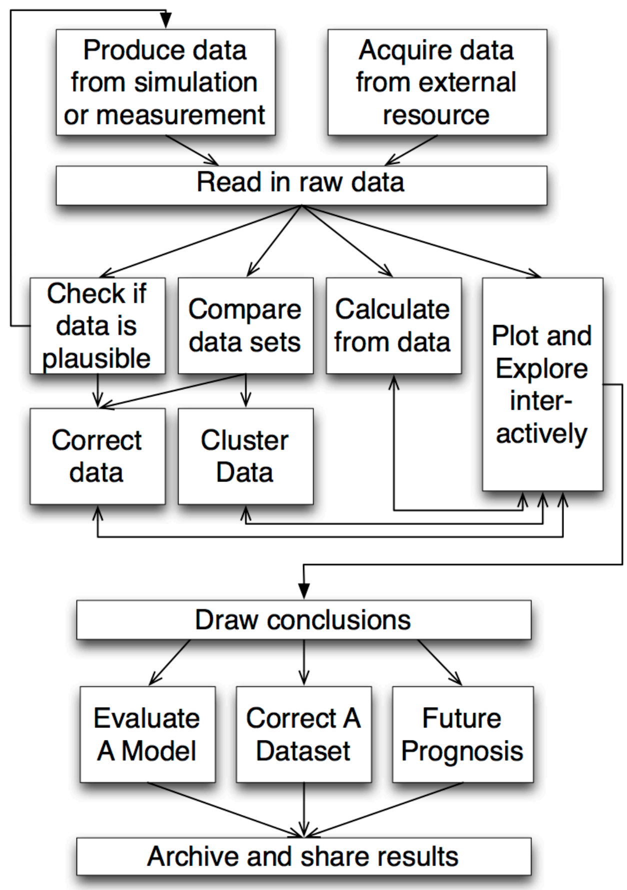

Figure 4.3. A general workflow of Climate Scietists by data analysis tasks

Fig.4.3. shows a common workflow summarizing the data analysis process in all three user groups. The task of data analyzing is very similar and can probably be generalized to other scientific disciplines as well. The first step is the acquisition of data, either from external research institutions or from their own simulations. This data has to be read into their software
environment. Then, often, the data is plotted, or otherwise checked for its plausibility, e.g., by scanning through the numbers by hand. Often, some data is derived from the raw data by calculations following some hypothesis.
Following the results of these steps, and potential plots of data, the original data are corrected or clustered. Results at this stage are always plotted and/ or explored interactively. From this, conclusions are drawn. The conclusions are specific to climate science, and can consist of either the evaluation of a model, the correction of a data set, and/ or some

future prognosis. Finally, results are archived and shared – for which usually the plots serve as a basis in
discussions and publications. The analysis shows that visual inspections are the key parts of the workflow. Therefore we argue that an additional auditory display can be helpful for the scientists to explore data from other perspectives.
The commonalities in each step (Data gathering, Data Analysis, Drawing Results) of the user's actions will help define features of the audio interface.

4.3.2. FOCUS GROUPS

Participants belong to three different research groups (ArsCliSys: Atmospheric Remote Sensing and Climate System Research group, ReLoClim: Regional and Local Climate Modeling and analysis research group, EconClim: Economics of Climate and Environmental Change research group). The structure of Wegener Center has changed since our first user studies, therefore we focus on the research groups at the time of each study. Each user group participated in a team discussion (focus group) where they shared ideas and opinions on their work. Focus groups were conducted to observe more specific information about the communication between the experts within a group and the language and metaphors they use. Participants brought their own task results and were asked to briefly present and discuss them with the other members of the team. The focus group discussion for each group took about an hour.

As a further qualitative analysis, both the interviews from the contextual inquiry and the focus groups have been analysed concerning their language content [Sch14]. On the correlation of words mentioned during contextual inquiry and focus groups, a small trend towards using similar vocabulary within the same research group is noticeable. The difference between the focuses of each research groups is reflected in the language they use. The active vocabulary used by the climate scientists and the number of different words mentioned by each person, does not necessarily correlate with their experience in the field, but rather with the general communicativeness of the person (which is measured by the totall number of words each person used.)

Furthermore, the words used by the scientists have been grouped. The categories for the groups have been determined iteratively, where final categories emerged while trying to group the data as far as possible.
As shown in Fig.4.4 the top four cited categories in the interviews are *data analysis*, *simulation*, *description of climate phenomena*, and *data properties*, which is not surprising because of the nature of the data analysis task the participants have been asked to demonstrate. Comparing the focus groups communication and the contextual inquiry interviews, it turned out that in the latter condition the scientists talked more about general phenomena and less about data analysis. Regarding the generalized categories *data* and *climate phenomenon*, it turned out that for data analysis the most important method is correlating or finding relations between two data sets. Also visual analysis is often used. Next, preparatory steps are important, including for instance data acquisition, listing, simple calculations, calibration, and transformation of grids, sorting and retrieval.

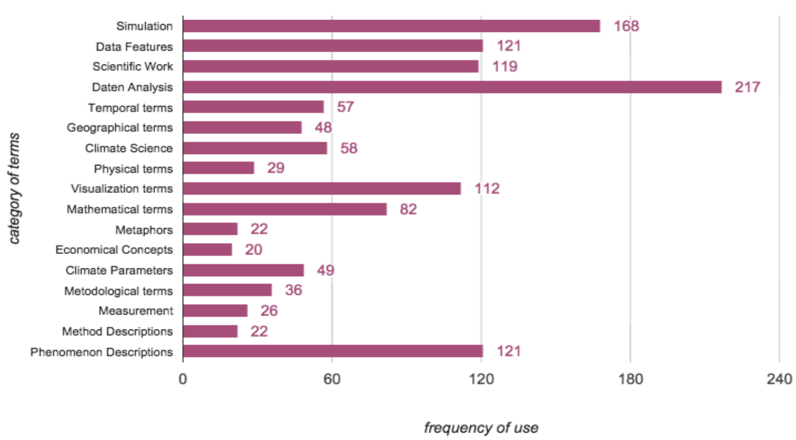

Figure 4.4. The most citet categories by climate scientists during the interviews

4.3.3. CONTEXTUAL ANALYSIS

We analyzed both the interviews from the contextual inquiry and the focus groups for their language content. Use of climate terminology helped us realize a domain-specific description of the sonifications that are useful in the field. Identifying metaphors can help build a metaphoric sound identity for the sonification. In a quick check on the correlation of word mentions, we found a small trend of using similar vocabulary within the same research group. The richness in vocabulary—that is, the number of different words mentioned by each person—doesn't correlate with that person's experience in the field.

In the next step, we grouped words into iteratively determined categories. The categories most often cited in the interviews were data analysis, simulation, description of climate phenomena, and data properties, which wasn't surprising, given the task the participants were asked to do. Comparing the master-master communication in the focus groups and the master-layman communication in the personal interviews revealed that in the latter condition, the scientists talked more about general phenomena and less about data analysis. We further analyzed the subcategories used by the subjects in both interviews and focus groups and found the following:

- Climate scientists use visualization as their main tool.
- Temperature is the most important climate parameter for these scientists.
- In terms of working style, programming is the daily job of most of the scientists.
- They use basic mathematics, for example, difference is in the top 10, the most important basic method when comparing datasets.

Regarding the generalized categories data and climate phenomenon, it turned out that, for data analysis, the most important method is correlating or finding relations between two datasets. After that, preparatory steps are important, including data acquisition, listing, simple calculations, calibration, and transformation of grids, sorting, and retrieval. When describing phenomena, subjects mostly used comparisons followed by logical, emotional (good/bad, interesting), and aesthetic statements (beautiful/not).

4.3.4. METAPHOR ANALYSIS

In general, we found few metaphors in the collected words. The participants used the standard vocabulary of science, which can't be interpreted as metaphors in the contextual analysis, but they become metaphoric when shifted to the auditory domain. In the following paragraph, the italicized words are the specific terms that could become metaphoric in the auditory domain.

Climate data is inherently dynamic: climate scientists run a simulation or collect time series data. Therefore, the general direction of reading the data follows from the time axis of the playback and is independent of the further processing, filtering, amplification, and so on that depends on specific sonification data. Periodicities and any associated type of wave phenomena play an important role in climate science and can be directly linked to sound oscillation and rhythmic phenomena. Resolution is a big topic in climate science when comparing different datasets or trying to find phenomena at a certain range; resolution in audio is given by the sampling rate, and it can be changed by interpolation, an approach scientists are used to as well, such as when fitting a plot. Missing data plays a large role in climate science; an obvious analogy is making it audible as breaks that can be used for a quick scanning of a dataset's completeness. The ensemble in climate science is a group of datasets resulting from different runs of a simulation. Because a single outcome is always the product of random processes, only the ensemble of many simulations can be regarded as trustworthy; in music, an ensemble is a group of different instruments—a metaphor that can also be used in mapping, such as different climate models to different sound timbres. Climate scientists who work with measurement data or with simulation data both know about the signal-to-noise ratio. One participant called the atmosphere noisy when a high amount of greenhouse gases was found there, and scientists search for long-term trends in everyday weather's noisy/random behavior. Although noise in climate data has a different meaning than noise in sound, it could be a useful metaphor in sonification.

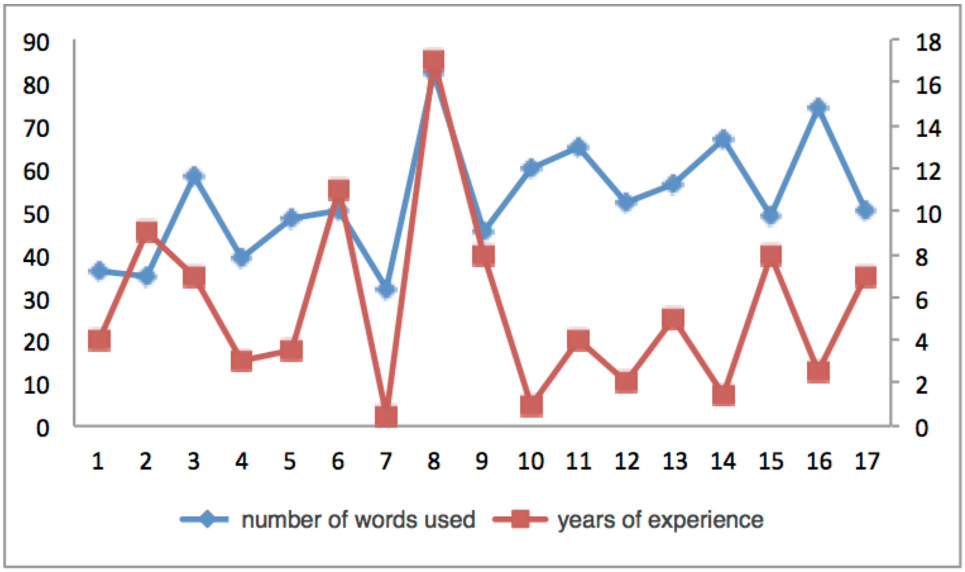

Figure. 4.5. The relation between the experience of climate scientists in the field and their use of words.

Obvious mapping strategies include the height dimension in climate data (altitude) to the height in sound (pitch), but temperature also has a tight association with pitch; the geographical spread can be used for spatial rendering in audio. Weather phenomena are linked to typical sounds and can be used (rain or wind sounds). On a more conceptual level, terms like extreme, dramatic, or beautiful will have to be transferred to the sound design and evaluated in listening tests by future users. Furthermore, the control of the audio interface will involve actions that climate scientists are used to anyway, such as calibrating or filtering data or sound.

4.3.5. USER STUDY ON SOUND PREFERENCE

In a set of studies sixteen participants from two groups (Climate Scientists and Sound Experts) expressed their preference of sound for an auditory display. They evaluated a set of sounds aesthetically on the first stage and associated them to climate terms on the second stage of the study.

In *The Soundscape* book [Sh93] Schafer defines soundscape as the sonic environment. Technically, any portion of the sonic environment regarded as a field for study. The term may refer to actual environment, or to abstract contractions such as musical compositions, particularly when considered as environment. In Sonification, soundscapes have been used to create a sound environment where separate streams of sounds fit together to shape an immersive environment, while transferring information about the data. Some recent examples include Hermann et al. real-time sonification of Twitter streams [HNE+12], and Boren et al. using ambisonic sound recordings from urban soundscapes as a layer in an auditory display [BMGR14].

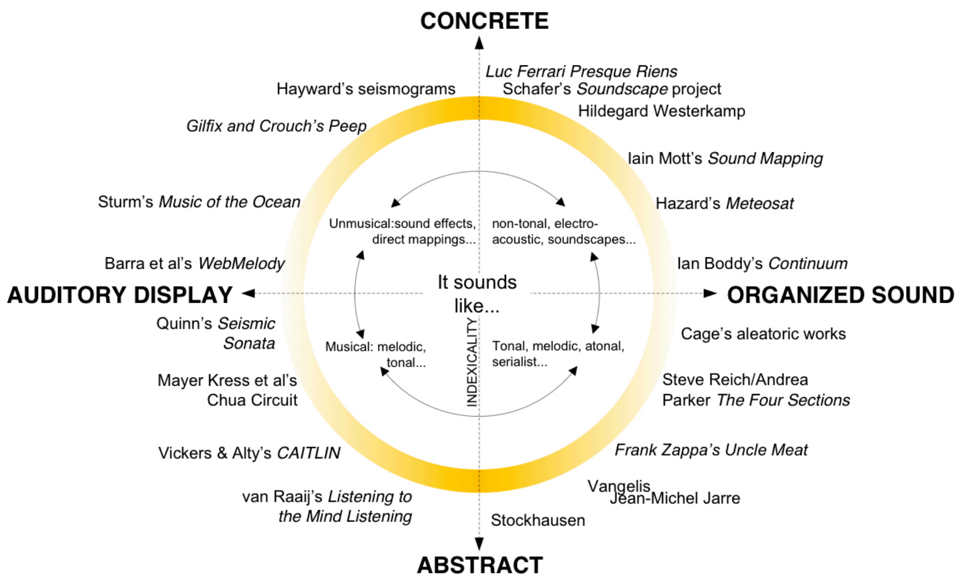

Figure4.6. The sound space

For this study 24 sound samples of 10 seconds duration each were used. All sound samples were chosen to support natural acoustic soundscapes especially climate related sounds. Mauney and Walker [MW04] found these soundscapes useful for sonification as they can be easily distinguished from the background and have even been found to be *relaxing* with the potential to be less fatiguing than other sound Interfaces [VLDF14]. They were chosen from freesound [AFFD+11] database (using freesound's indexes) so that each three would constitute a group thematically or metaphorically connected to one of eight climate parameters determined in workflow analysis of climate scientists: *Temperature, Precipitation, Air Humidity, Pressure, Geopotential height, Refractivity, Radiation,* and *Wind*. The reason for this selection was to provide a broad range of sounds which can be used to elucidate whether the climate scientists will be able to associate these sounds to parameters of their domain, and whether this association is unanimous. Each study was divided into two sections; the purpose of the first stage was mainly to evaluate the sound samples (stimuli) aesthetically, and the second part for mapping the stimuli to the climate parameters. Altogether each experiment took between 35 to 45 minutes. The participants were given identical settings, listening to the stimuli via the same type of headphones. Participants were presented eight groups of three stimuli. After listening to each group of each three in a dissimilarity rating, they were supposed to indicate which of the three they liked the most on a scale from 1 (“not at all”) to 9 (“very much”). Furthermore they were asked to describe the characteristic that they liked about it. In the second round, they heard the same 24 stimuli one after another but with a random order. They were handed a list of climate related parameters and for each sound sample, they were asked to choose which parameter best correlates to the sample they just listened to. Each sound stimulus was about 10 seconds and there was a 10 seconds break between successive stimuli to give the participant time for evaluation or mapping. In order to compare the effect of auditory experience and music knowledge on evaluating the aesthetics of sounds, the experiment was repeated on two different groups of participants. The second group were all sound experts from Institute of Electronic Music and Acoustics (IEM) at University of Music and Performing Arts in Graz . Each group consisted of 8 participants. The project and the goals of the experiments were briefly explained to both groups before the experiments. Additionally, the climate parameters were briefly explained to the sound experts since they did not have the domain knowledge.

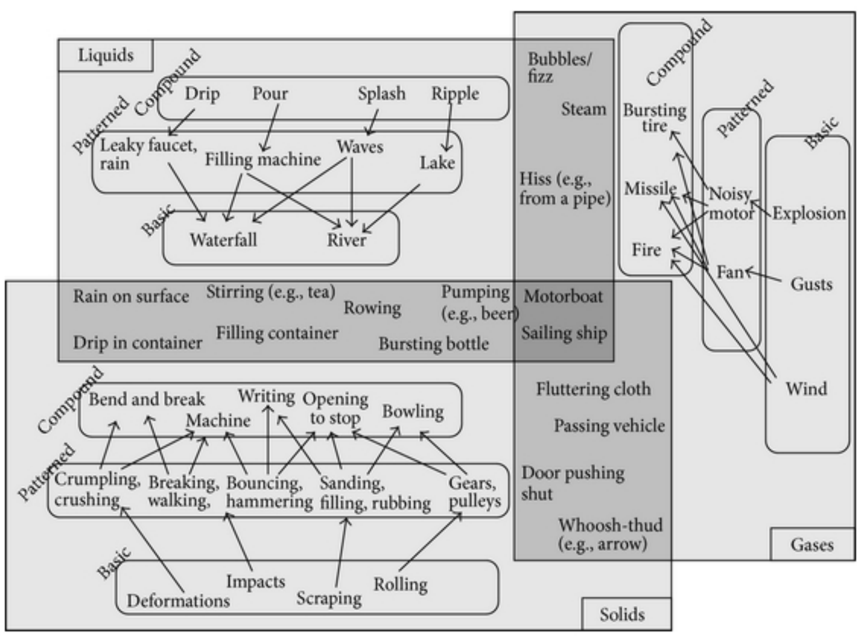

Figure.4.7. Gaver’s Taxonomy of Sound

4.4. DISCUSSION

In terms of a systematic design process, we are considering tracking the interaction of sound experts with tools as well as the interaction of climate scientists with the framework. We plan to study several aspects found in the analysis of climate data, such as comparing models, highlighting regions, showing differences and error boundaries, adding threshold guides, and so forth in terms of potential analogues in the auditory domain.

5 SYSSON FRAMEWORK: DESIGN

5.1. REQUIREMENTS OF THE SOFTWARE FRAMEWORK

The main design aim is to allow development of new and modification of existing sonication designs. By using modular software design which decouples components like basic data handling objects, data processing, sound synthesis processes, mappings used, playback approaches, and real-time interaction possibilities, all the individual aspects of one sonication design can be re-used as starting points for new designs.

5.2. FRAMEWORK, STRUCTURE, AND USE CASES

The workspace for SysSon platform is called Mellite provides a graphical user interface for Sound Processes and defines the workspace as the basic organisational unit. A workspace in most cases is simply a root folder that can be thought of as the main “patcher”. The creation and modification of objects inside this patcher are automatically synchronised with an underlying database. We thus ensure that the user can come back to the workspace at any later point and will find everything in its previous state, including for example the parameterization of sonification models or plot objects. To preserve state, one can either duplicate objects or use an automatically versioned workspace that traces the evolution of all parameters over time.

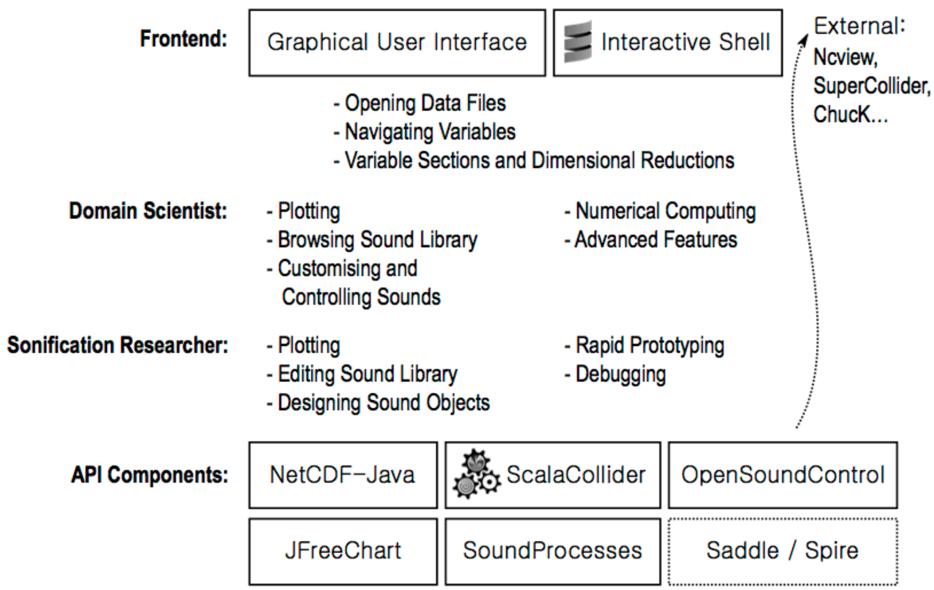

Figure 5.1. Architecture of SysSon platform

The GUI uses metaphors of a standard desktop application such as point-and-click, drag-and-drop, and undo-redo. Fig.5.2 shows an example workspace containing data-sources, sonification models, an audio-file and plots. Except for locations and audio-file, these are objects introduced by the SysSon platform.

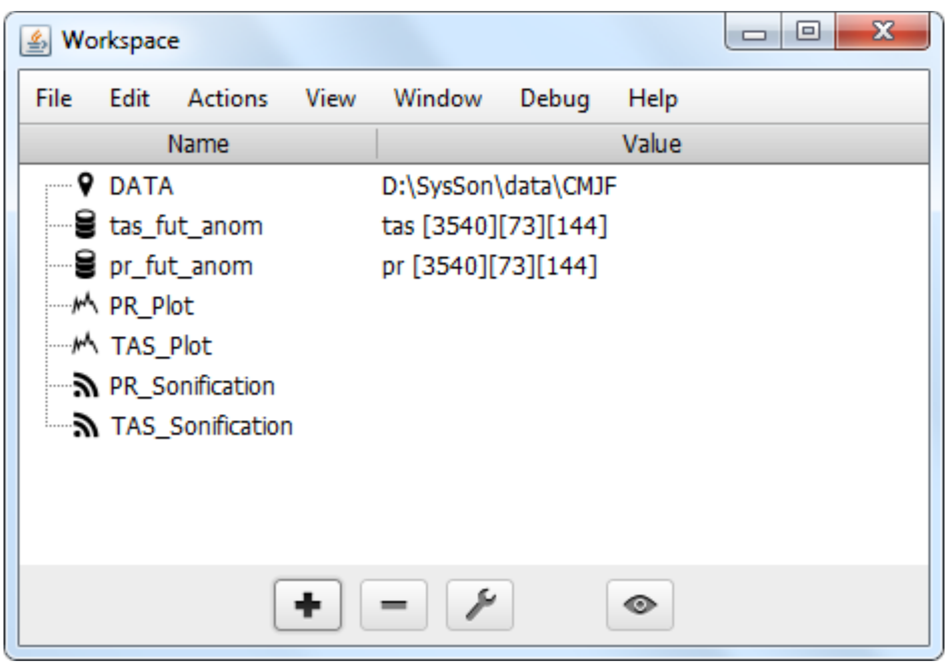

Figure 5.2. Workspace of SysSon platform

5.2.1 DATA SOURCES

ata sets for sonification can become very large, and domain sciences have come up with file formats to store them. SysSon supports NetCDF (Network Common Data Form) [JS92], a format frequently used in atmospheric research. NetCDF files can easily grow to several hundreds of megabytes, and they are therefore not copied but merely linked to workspaces as external references through handles called data-sources.

When a data-source object is created, its skeleton structure consisting of a number of variable descriptors (matrices) is stored with the workspace, allowing operating even when the underlying NetCDF file is offline. A data-source is associated with an artefact, which can be updated when a workspace is moved to a different computer. Adding different types of data-sources in a future version should be simple. For example, at the moment a CSV file would have to be converted to a NetCDF or audio-file first, but there is no reason one could not add direct support.

5.2.2 MATRIX STRUCTURE

A matrix is a regular one- or multidimensional structure of floating point cells. Dimensions are simply represented by other matrices. For example, a matrix of precipitation data may have dimensions lon (longitude), lat (latitudes), time (time-series). Each of these dimensions then is another one-dimensional matrix (or vector) that stores the dimension's values, such as the series of latitudes with unit 'degrees-north'.

Matrices are composed and transformed through a data-flow graph. They usually originate from a data-source object. To be editable in the user interface, a variable placeholder is used that stores the current data-flow graph. Transformations then become new nodes in this graph. The most common transformation is a reduction of the matrix's size using a reduce object. The reduce object takes an input matrix, a dimension-selector and a reduction operator.

For example, to produce a time slice of the aforementioned precipitation matrix, the dimension-selector would indicate the time dimension and the reduction-operator is an index into the time dimension. The output matrix thus has a rank of one less than the input matrix. Each of the objects related to the reduction is again made editable through data-flow variables holding the dimension's name and the index integer position.

Other operators take slices (ranges) of a dimension or perform sub-sampling by skipping samples using a stride parameter. Future versions shall include other commonly used operators such as dimensional reduction through scanning and sub-sampling using averaging or interpolation, as well as binary operations such as taking the element-wise differences between two matrices.

5.2.3 PLOTTING AND SONIFICATION GUI

Plot objects encompass a matrix, a mapping from dimensions to axes, and visual parameters such as colour palette and scaling. Fig. 5.3 shows an example plot of a time slice of precipitation data.

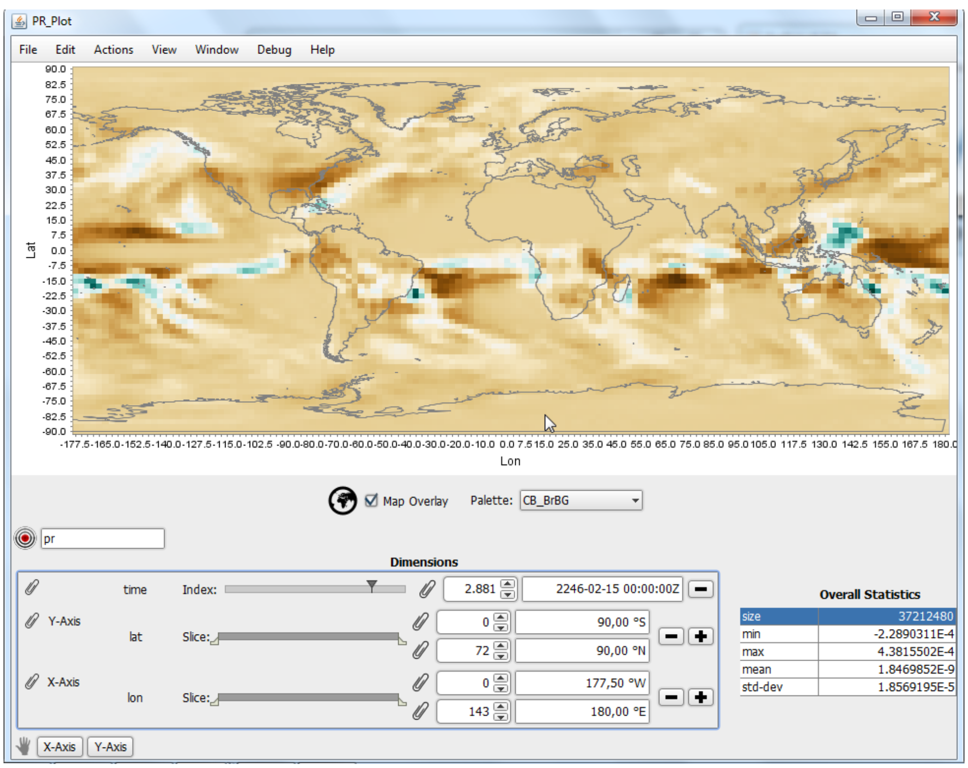

Fig. 5.3. Plot View

Sonification instances are encapsulated by a dedicated object type.

This object is composed of

- A sound process object that describes the sound production in terms of a synthesis function.

- A dictionary of sources where a logical name in the sonification model is associated with a tuple of a matrix and a dimensional dictionary. The dimensional dictionary provides logical dimensions for the sound model that may want to use them for unrolling the matrix in time or to drive specific sound aspects such as timbre or spatialisation.

- A dictionary of controls, which are user adjustable scalar parameters of the sound model. For example, a typical control would be the speed at which a sonification traverses a time series.

The user interface for a sonification object is shown in Fig. 5.3. The section labeled ‘Mapping’ shows that the model uses a single source ‘data’ with which a matrix ‘pr‘ has been associated. This matrix has been reduced. The model also defines two logical dimensions ‘time‘ and ‘pan’, which are associated with the matrix’s own ‘time‘ and ‘lat‘ dimensions. Using this dictionary-based decoupling, sonification models can be flexibly tested with different data inputs.

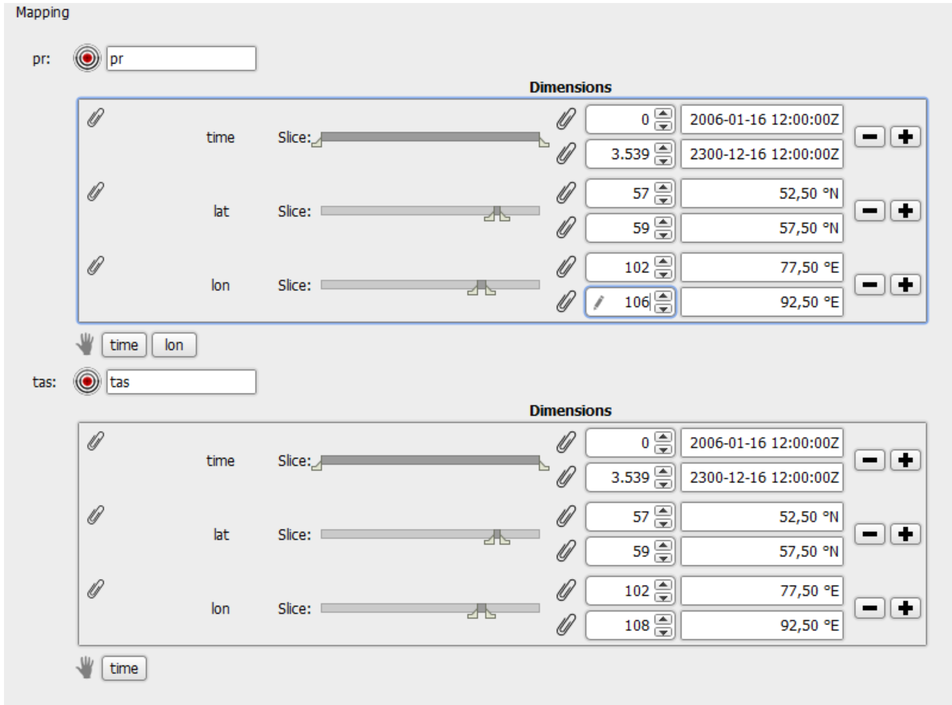

Fig. 5.4. Sonification View

The sonification researcher or sound designer can open an integrated code editor within the workspace to develop the sound models. Regular ScalaCollider expressions are augmented with user interface elements such as the ‘user-value’ object responsible for the ‘controls’ section of the sonification editor, and data specific elements such as matrix and dimension keys. Within the DSP graph, matrices and vectors may appear as scalar values or dynamic time-changing signals. When a sonification object is made audible, the system translates the matrix expressions into a cache of audio files, which can then be streamed on the SuperCollider server. We exploit its multi-channel expansion feature and provide pseudo-UGens to easily align the matrix data with related data such as the axis dimensions.

5.3. USABILITY TESTS

After the SysSon software was at a usable level, we took it to the climate scientists for a set of usability tests. Eleven qualitative interviews (verbal protocols) with volunteer climate scientists from Wegener Center (4 female/7 male) from three different research groups and with varying degrees of qualification (see Tab.1) were conducted in German. One of these was obscured because the participant (m) did not talk loud enough, a second later excluded from analysis (because the associated research group was too different from the rest) yielding 9 interviews for further analysis. For most cases (except for one), two interviewers were present, with one interviewing and the other observing (and occasionally also asking questions). Participants were asked and encouraged to think aloud and describe what they were doing. Semi-structured interviews were conducted parallel to participants exploring the tool, comprising questions regarding user surfaces as well as interpretability of sonified climate data. The interviews consisted in part of a walk-through description of the tool, which usually (but not always) was not limited to brief introductory statements at the beginning of each experiment, but continued throughout. No standardized explanation procedure regarding the function of the platform was provided, though. Each participant was asked to indicate their respective field, as well as their qualification and previous experience with sonification.

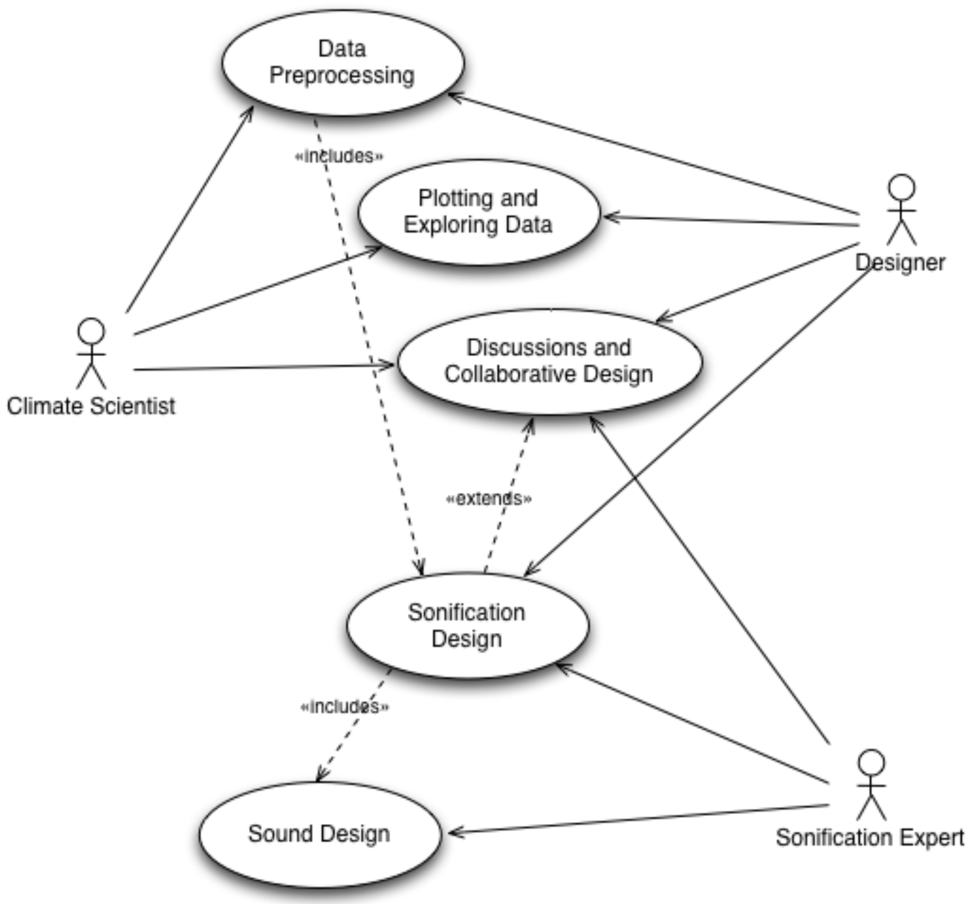

Figure5.5. A use case of the interactions of the users, end users and the SysSon platform.

Bonebright/Flowers (2008: 112) suggest that experimental procedures should be developed according to the particular goals of a sonification application. The experiment was designed so as to emulate the "natural" workflow of the climate scientists. To this end, atmospheric temperature at surface level was chosen as the sample data parameter because this particular parameter is of interest across all research groups that we studied. The user studies were not carried out in the climate scientists' working environment. Instead, they were conducted with each participant individually, providing our laptop as mobile work station. We focused on one sonification task we believe to be the most relevant for climate scientists from different research groups according to the Contextual Inquiry, namely a comparison task. However, comparing different climate models or different data sets is time-consuming and made an hour-long user study impossible. Therefore we decided to make comparisons within a specific data set in two different geographic regions. This gave us the chance to explore the interaction of the participants with the software.

Two tasks were scheduled: in the first, participants had to find two different, given locations in the plotting interface, and navigate in the sonification interface to the same locations. In the second task, the sounds of the two locations had to be compared, and participants could explore the sounds freely (also possibly changing the location). They listened to parallel sonifications, either varying the time axis or the geographical dimensions (latitude and/ or longitude). They were asked to open two workspaces simultaneously and then to design two sonifications to later listen to. However, due to limitations of the then current software implementation, strictly parallel listening was impossible. Accompanying questions regarded the interpretability of sonified data as well as possible uses within climate scientists' respective fields of interest. Participants were free to listen to the sonifications for as long and with as many repetitions as they wished. They were asked to listen carefully and also to interpret what they heard regarding information about temperature (in the same way they would interpret visualizations).

In total, three different types of documents were generated: audio recordings of the experiments, transcripts of the recordings and field notes of the interview situations to capture non-verbal aspects of the interviews. The transcripts and the field notes were then coded for detailed analysis using Grounded Theory. All experiments were audio-recorded and transcribed (except for one) using f4 and an adapted version of the transcription guidelines recommended by Kallmeyer/Schütze 1976 to accommodate to the specificity of the interview situation (participants listening to and replaying different sonifications with only occasional comments, which means lots of "dead air" throughout all interviews; these passages were encoded as "playing sonification"). Short, unsystematic observation protocols were drafted of most sessions, capturing aspects of the interview situation to facilitate analysis. However, these protocols have proven difficult to analyze systematically – listening to the audio recordings would have sufficed to make similar observations about the interview situation. In what follows we describe the user experiments. Participants were first given a brief introduction, including a description of the experiment as well as an introduction to the sonification software. Then, they were asked to open a data set (in this case, the near-surface air temperature as projected in a global climate model from 2006-2300). The instructions given to participants were standardized as much as possible to eliminate interviewer influence. Two pilot tests were held at Wegener Center to ensure that the instructions were clear enough. These were not included in the analysis.

Classification	Category	Number of Participants
Research Group	ReLoClim	3
	ArsCliSys	8
	EconClim	1
Gender	Male	8
	Female	4
Qualification	MS	1
	PhD	5
	PostDoc	3
	Professor	2
	Engineering Staff	3

Table 1: Participants of the Usability Tests

5.4. DISCUSSION

The results of the usability studies can be grouped into two categories: data concerning usability proper (comments on the functionality of the sonification platform) and attitudes on sonification in general. We describe them in turn. Analyzing notes and observations from usability studies, three categories of usability issues were gathered: visualization, sonification, and navigation. Each category comprises several issues to be tackled by improving the software in the next iterations (see Tab.2 for details). Some functions in the plotting window were missing such as zooming, scaling, changeable color scheme, and indexes for latitude and longitude. Concerning the sonification window, the climate scientists expressed their desire to have options and controls such as mute and pause buttons. Navigation throughout the platform was challenging for the participants. One of the main problems the climate scientists had concerned the “plus/minus“-buttons (+/-) on the sonification window. The purpose of these buttons is adding slices or strides of a data parameter to the sonification. The use and interaction with them was not intuitive. A further navigation issue concerns the lack of a temporal display showing the time currently sonified. Visualization issues included the color scheme which was considered ambiguous. Climate scientists deemed a more standard color scheme desirable. Sonification issues concerned, among other things, the options for simultaneous playback of two data sets as well as different slicing options.

Usability Issue	Sub-Category
Plotting Window	- Zooming and Scaling - Color scheme - Indexing Latitude/Longitude
Sonification Window	- Options and Controls - Slicing
Navigation	- "plus"-button - undo options - file paths/ directories

Table 2: Usability Issues found during the user studies

The questionnaires used in Contextual Inquiry focused on understanding how climate scientists work in general and how open they are to use an auditory display in addition to their visual tools. Additionally, understanding their visualization tools and their workflow was another central point. In the Usability Testing, the questions were more task specific and focused on usability and learnability aspects of the SysSon tool. The cultural bias towards sonification was observed indirectly by recording the interactions of the climate scientists with the tool and their impressions on what the data sound like.

In Contextual Inquiry the climate scientists' suggestions on sound for sonifications were mostly based on mapping a climate parameter to pitch or loudness in an oscillator or pulsing signal. Only one climate scientist suggested noise for articulating higher humidity in atmosphere. In the Usability Testing the suggested sound was an oscillator, which was received very understandable and intuitive for the climate scientists. No one found the sounds annoying or draining. Inferences to the sound quality are not feasible, however, due to the duration of the experiments. Working with the same sounds for longer time periods would in all probability yield different results.

In what follows, we describe the attitudes toward sonification that the climate scientists in our sample expressed during the usability studies. Here, we discuss the most significant findings.

- There is a considerable portion of skepticism vis-à-vis the sonification of data in general in the group we studied. This skepticism concerns issues of temporality (sound is a temporal medium, which may lead to difficulties when comparing within a given data set) as well as learning and applicability: "Well if you use the entire data set, the entire time slice, it's relatively difficult to compare what you heard at the end with what you heard at the beginning." "You really need to be more familiar with it to be able to hear something out of it." "Well I think it wouldn't help me in my work. […] Well I, well it's, it's a nice tool, but I don't think I, that it's applicable for a bigger domain." However, these findings are somewhat contradictory if compared to others from the same sample, since climate scientists are well aware that both visualization and listening are learned. Also, comparison across different data sets as well as within given data sets was suggested as a task where sonification could be very useful.

- The climate scientists see strong potential for using sonification in conjunction with visualization, e.g. comparing sonifications and visualizations of the same data, either using sonification to display some dimensions and visualization to display others simultaneously: "I think it would be interesting if you could simultaneously visualize it a bit. To be able to see the whole region like a movie would give you a different access to understanding such data."It would really be interesting to both look and listen at the same time." „Well I would prefer it if both were connected somehow. I would regard sonification as another dimension of graphic representation." "Well I would like to have the option to look at it at the same time."These passages suggest that sonification is not regarded as a method in its own right, but rather as a supplementary device in addition to visualization.

- Climate scientists would use sonification for getting a quick initial overview of large, complex datasets. However, the results also suggest that some of them have a very simplistic idea of what is and is not possible with sonification: "[…]whether that would otherwise be helpful to just perceive basic structures or the basic tendency the first time."Like, where I wanted to hear what that sounded like as quickly as possible“ “When you do the first data check. To discover irregularities. To basically just put on your headphones and listen to the data. That you get a feeling for whether they are plausible.”

- Climate scientists would use sonification to present some dimensions of a complex dataset and visualization for others. When different climate models have to be compared with regard to predictive power, the amount of relevant data becomes even greater. Climate scientists see a potential for sonification to deal with this increased amount of data (i.e., reduction of dimensionality to facilitate data display and exploration): “Or, what would naturally be good for the sonification, what I could imagine for the sonification is, if we get data sets, we usually work with ensembles of data sets, which means we don’t just have one model but often fifty. Plus multiple simulations of each model. Huge amounts of data.” “What do I hear in the data, do I hear the same in the models? That is an interesting application.“ “I mean in climate science generally you have a lot of statistics. And it is always averaged over time, or over, well, you look at processes and for that it’s definitely interesting. How well the models can do that, represent certain processes. Especially what they right now, let’s say climate model-based climate science, that is, that has potential, I think.” “Well if one could get help, one of the two dimensions or one of the three dimensions, if you have long, lat and time […]“ „Well the difficulty is really like to conceive the spatio-temporal variability at the same time. If you could help us here with one of the two or three dimensions, if you have long, lat and time...but that will be difficult. Because, eventually, each data point has its own timeline.”Additionally, climate scientists see more potential for sonification to illustrate the temporal dimension of their data than other dimensions. Climate scientists believe that sonification could facilitate the recognition of minute changes of patterns in the data: “Plus, you average over the time slice, or over, well, you disregard time, look at processes and for that it’s certainly interesting.” “The strength of sonification is probably to hear variability.“ „Whether you recognize a pattern that is simply dislocated, if you compare it with other data.“

- Climate scientists are aware that the ability to use visualization and sonification are both learned. They are aware that they have an enormous amount of training in visualization and hardly any in

> sonification. The climate scientists think that sonification might become equally useful if they had an equivalent amount of training in both approaches: “There are hundreds of years of research in it, how to visualize and how to look at it closely. And the other thing [sonification] is still in its infancy.” “We are simply used to doing a lot via the eyes.”

The analysis of user tests shows clearly that the scientists have gained a relatively realistic picture of the advantages and drawbacks of sonification. The scientists would like a tool for quick overview, to check the plausibility of the data; a tool that complements their visualizations and helps to cope with the high number of data points and/ or high number of data dimensions; they acknowledge sonification as being especially apt for temporal data (which is often used in climate science); the scientists understand that it takes time to learn to parameterize and listen to the sonifications

6 COLLABORATIVE AND PARTICIPATORY DESIGN

6.1. COLLABORATIVE AND PARTICIPATORY DESIGN AND THEIR USE IN AUDITORY DISPLAY

Analysis of requirements and constraints, and understanding the users in the context of the systems functionality and the tasks that she is involved with are the key constituents for a successful design process. The concept of Task and Data analysis (Tada!) was first introduced by Barrass [Bar98] as the first step for auditory information design. Tada! includes some crucial aspects of how to design an auditory display for a specific task, based on descriptions of the task and data, but it has limited applications. In Tada! what is going to be perceptualized using auditory display is known in advance, whereas in many domain sciences an exploratory approach is required without knowing exactly which features or patterns in data to look for. Additionally, Barrass [Bar03] and Frauenberger [FS09] explored design patterns in the sonification field.
Frauenberger showed that the design process for auditory display is mostly unstructured and it provides limited support to reuse the design knowledge created. Another issue is that methodologies and existing guidance in the auditory domain are often affiliated with a specific context and reusing them is only possible within the specific context [FTB05]. A sonification tool as a general software package to develop quick sonification designs for a wide range of scientific domains has been explored by deCampo et. al [deC07]. Other tools, such as Sonification Sandbox [WC03] or SONART [BBCD+02] have investigated a smaller range of applications. In our approach, we wanted to focus on a specific domain (climate science) and context (as Flowers et al. suggested) but giving a broad range of sonification design possibilities to the users and the power of designing sonifications. Sonification of scientific data requires understanding and expertise in the domain science, sonification design, and computer science. In order to create useful sonifications, experts design and develop sonification systems iteratively working with the domain scientists. In project SysSon, we proposed an approach to allow our users (domain scientists) to take control throughout the design process. The main concept of the project was to create an interdisciplinary sonification platform which enables climate scientists and sonification researchers to generate sonifications systematically. Climate

scientists from Wegener Center for Climate and Global Change provided a huge variety of measured and simulated climate data for this research project. The starting point for our approach were previous interdisciplinary sonification workshops which had a broader user group than our project. The Science by Ear [dDFV+06] workshops had domain scientists from different scientific domains with a variety of data (e.g. medical data, sociological data, physics data.) Our focal point was one specific domain with the variety and complexity of data sets and problems within this domain. Contextual inquiry and focus groups were conducted in the climate scientists workplace to gather information on climate scientists' workflow and data analysis tasks. Considering the results, a sonification platform was designed and developed. The development has been an iterative process and involved the users greatly at all stages of the design and implementation. In order to produce a wide range of sonification examples within the sonification tool using different data from climate scientists, we conducted a multi-disciplinary workshop. This paper describes the objectives, methodologies, and outcomes of the workshop in detail. It entailed collaborative work between climate scientists, sonification experts, and programmers.

Creating a sonification platform to analyse scientific data that is user-friendly, efficient, and effective requires a broad knowledge of the domain science. The knowledge to understand, frame, and solve problems in the domain science is not given, but is established and evolved during the design process. In such an iterative process, users become co-designers not only at design time, but throughout the whole existence of the sonification system. Rather than presenting users with closed systems or predefined sonifications, we planned an iterative system design that evolves by user's engagement to explore and design a variety of sonification possibilities for their problem domain. This allows the users to extend the system to fit to their specific tasks and needs while being assisted by sonification experts in this process. We partially used user-centred [ND86] and participatory design, but we extended our approach in parts to meta-design [GF08] to shift some control from designers to the domain scientists by empowering them to create and contribute their own objectives in the sonification design method.

A sonification system for analysing data is a living entity which evolves during and after the design process continuously. Thus, the participation of the users in the design decisions go beyond the processes at the design time. We also included participatory design [SN93] to involve users in the co-design process with the sonification designers. Despite the advantages of participatory design during the design time, sonification systems need to be evolvable to fit new needs and tasks created by users after the completion of the system. Therefore, we needed the domain scientists to be fully involved to contribute and modify the system themselves when new needs arise. Nevertheless, the sonification design space is huge and impossible to be explored by novice sonification designers.

Thus, during the workshops we focused on specific use cases that represent a variety of domain scientists workflows to explore the design space. The SysSon approach is an open framework for sonification researchers and climate scientists to develop a variety of sonifications but also having the option of using default mappings of climate parameters to sound parameters, suggested by experts. Fig.6.1 shows the scheme of collaborative and individual spheres for climate scientists and sound experts (sonification experts and audio programmers) within SysSon platform.

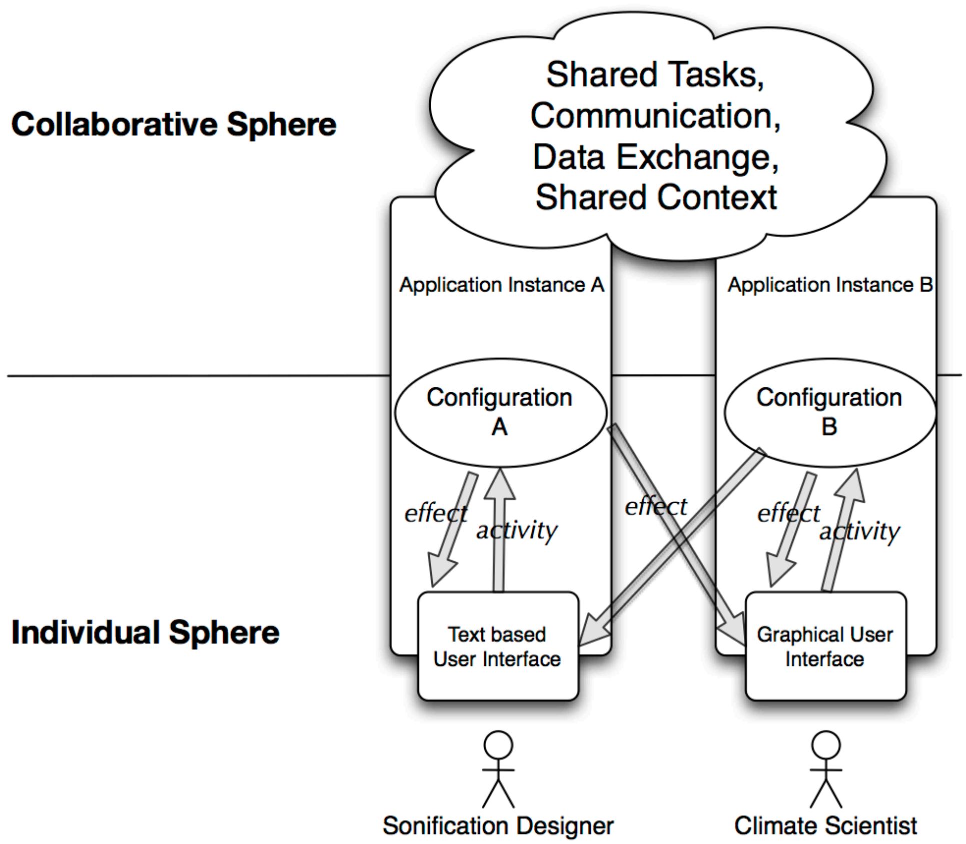

Figure 6.1.Collaboration between Domain Scientists (Climate Scientists) and Sound Experts in a Shared Context Scenario

6.2. SBE3 (PARTICIPANTS, METHOD, PROCESS, DISCUSSION)

As described in the previous section, a combination of user-centered and meta design is used to collaboratively create sonification solutions to the climate scientists' problems. This collaborative research process was compacted into an experimental Climate by Ear workshop process. The multidisciplinary workshop was two and a half days long and it brought together sonification experts, climate scientists, and audio programmers. There were 4 climate scientists, 6 sound experts (3 out of 6 Professors), 7 males and 3 females in the workshop. The participants were from different levels of expertise in their field. 4 PhD. candidates, 2 PostDocs, and 4 Professors were present at the workshop at a time.

At the beginning of the workshop, the project team introduced the project and the sonification platform. A climate scientist from the project team also gave an introductory lecture on climate data and the data sets that were going to be used during the workshop.

Afterwards, participants were divided into two groups. The groups changed by each task. In each group, there was at least one project member, one or two audio programmers, two climate scientists, and one or two sonification experts. The workshop was divided into hack sessions within groups and discussions between all groups at the end of each hack session. Hack sessions lasted between 2 to 4 hours.
The hack sessions entailed the development of three tasks that included sonification strategies and experimentation with the SysSon platform via iterative coding. Some scripts for data input and basic sound synthesis routines were prepared in advance to allow participants to focus on the sonification design process.

During the first session, both groups worked on the same task. By the second and third sessions, each group was structured to work on a separate problem to allow a variety of tasks to be explored. Each group started tackling the task by brainstorming and identifying potentially more interesting research questions for the climate scientists within the data sets used in the task. Then sonification experts introduced some ideas and the sonification design process turned into a more collaborative and experimental approach. The dynamic and experimental nature of the collaboration made it more difficult to stick to the pre-defined tasks and finally each group either focused on the data and research questions that were more interesting for the climate scientists in that specific team, or were more manageable to sonify within a short amount of time for the audio programmers.

6.2.1.FIRST SESSION

For the first task, we used near surface temperature and precipitation data in monthly means (one value/month) over 156 years in the past (1850 - 2005) and 295 years in the future (2006 - 2300). The goal for this task was to scan temperature and precipitation data and listen to both simultaneously to find different patterns in various geographical regions. We wanted that teams make decisions on how to read through data dimensions, chose specific regions or global data, find metaphoric sonification designs to distinguish between temperature and precipitation changes, and compare the zonal data sets to the full range of data sets.

GROUP A Strategy:

The sonification approach for this task was parameter-mapping using granular synthesis. The group restricted themselves to a specific region. Some ideas that were implemented in this group entail:

- Using pitch and amplitude to perceptualize precipitation level.
- Keeping the density of the grains fixed.
- Using upward glissandi for north, downward glissandi for south mapping.
- Using panorama for east - west mapping.
- Using noise gate to display only data above a certain threshold.

The climate scientists suggested to combine multiple parameters because one parameter alone does not represent extreme scenarios in climate. Precipitation is not linearly distributed and shows only a few outliers and it sounds pretty uniform in one area. Thus, it needs to be displayed over broader regions. Examples of sonifications created during the workshop could be found on the workshop's wiki: https://github.com/iem-projects/sysson/wiki/ClimateByEar.

GROUP B Strategy

This group decided on convection areas, e.g., Monsoon areas, where temperature and precipitation are highly interacting. For their first attempt, they tried to sonify data from the Himalaya region with panned longitude, latitude as frequency, and density as rain. They also explored the sonification of different regions. For instance: temperature seemed to be very stable in Northern India in the sonification which is not true. Then they chose a new region, where there is more variation in both temperature and precipitation such as Boulder, Colorado.

The grid resolution of the data might have been too coarse for the task in order to calibrate the sonification properly. Thus, the sounds created during this task did not meet the expectations of the climate scientists.

6.2.2. SECOND SESSION

As mentioned before, for this session we did not use the pre-defined data sets and tasks. Instead, the climate scientists in each group discussed what are some of the more challenging and interesting phenomena they would like to analyse using sonification. The structure of the workshop was very dynamic and the participants were in different groups during each session.

GROUP C Strategy

This group consisted of more climate scientists who work with radio occultation (RO) data sets. The RO method is a remote sensing technique making use of GPS signals to retrieve atmospheric parameters (refractivity, pressure, geopotential height, temperature) in the upper troposphere-lower stratosphere (UTLS), which is defined as the region between around 5km and 35 km height.

The group focused on the quasi-biennial oscillation (QBO); a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 28 to 29 months. An extratropical QBO signal should be hearable at higher latitudes with a different phase. Reading and processing data for this task took most of the time of this session and the group managed to finish an Audification of the data.

GROUP D Strategy

This group adopted the sonification patch of the first task (including a monthly/yearly reference to display the time passed). They focused on finding interesting patterns in the El Nino region: -170 degrees South to +120 degrees North (Equator: +/-5) They tried different frequency mappings and examined a high density of sound grains with a randomly chosen dataset. Through experimenting by slowing down the playback time, playing grains with higher densities, and tuning the frequency, the resulting rhythmic patterns got more hearable.

Using granular synthesis for both temperature data and precipitation data made it difficult with quick playback to hear the synchronicities, because the precipitation grains are longer than the temperature grains and some patterns got masked. Then the group tried a different approach by changing the mapping polarity of precipitation sound because low precipitation as very high pitches was not very useful using this granular synthesis. (Examples could be found on the workshop's wiki page)

6.2.3. THIRD SESSION

GROUP E Strategy

This group explored using climate model data - future projections for temperature - to examine atmospheric variability patterns in climate model projections (e.g., Monsoon.) The data used was from three different sources for two different scenarios from the time frame 2006 to 2100. Some problems that the group ran into were that within such small datasets they were not sure if the difference between the two models is hearable at all. It was not clear if the problems are generated by the sound synthesis patch or from data reading complications. Another challenge was the limitation of the programming language (ScalaCollider) we were using throughout the workshop regarding sound synthesis capabilities. ScalaCollider is a SuperCollider client for the Scala programming language. Since the sonification platform we were using is built in Scala, ScalaCollider was used for the user side. ScalaCollider is still an experimental system which reduces functionalities comparing to

SuperCollider and provides higher level abstractions. The documentation is also very sparse which makes the learning curve, especially during a workshop, steeper.

GROUP F Strategy

This group tried to sonify wind data. The main question to answer in this task was how to display a vectorial value. The approach was to map timbre space to represent vector's angle (e.g. North-South direction as rising-falling sound; East-West as Crescendo /decrescendo sound). Exploring wind data took so long that this session was finished without any completed sonifications. The discussion continued with the other group the next day and all participants together finished a patch for this task collaboratively which could be found on the workshop's wiki.

6.2.3. PRE AND POST QUESTIONNAIRES

The participants of the workshop filled out a questionnaire before and after the workshop. The format of the pre and post questionnaires were the same but the content was slightly different.

The aim of these questionnaires was to get an overview on the participant's familiarity with the basic concepts of the other discipline before and after interacting and working with people from the other domain.

In both questionnaires, each participant was supposed to describe six words related to climate science, six words related to sound, and five words that could belong to both domains. The words were ordered randomly and there was a different set of words given in pre and post questionnaires. The climate words were chosen from the results gathered by the preliminary Contextual Inquiries mentioned before. The list of words used in the pre-workshop questionnaire is illustrated on Fig.6.2.

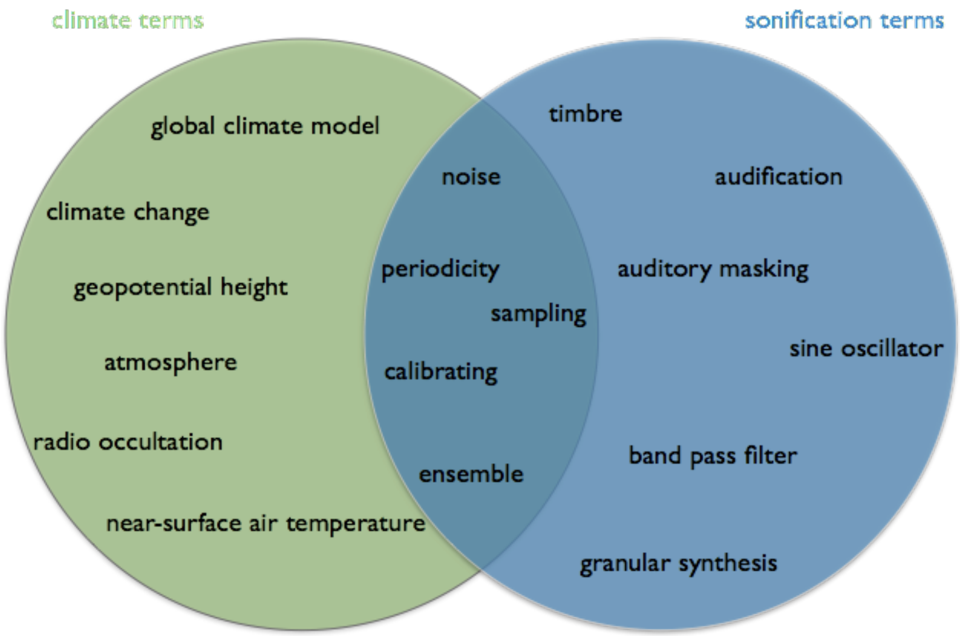

Figure.6.2. Domain Specific Terms used in Pre-Workshop Questionnaire

Results from pre and post questionnaires showed (Fig.6.3) that the number of correct answers regarding the other domain improved only slightly for climate scientists after the workshop. However, there was no statistically significant outcome in our analysis due to the small number of participants. Additionally, there were setbacks in responses of sound experts regarding climate terms and neutral terms after the workshop which we estimate to be because of fatigue.

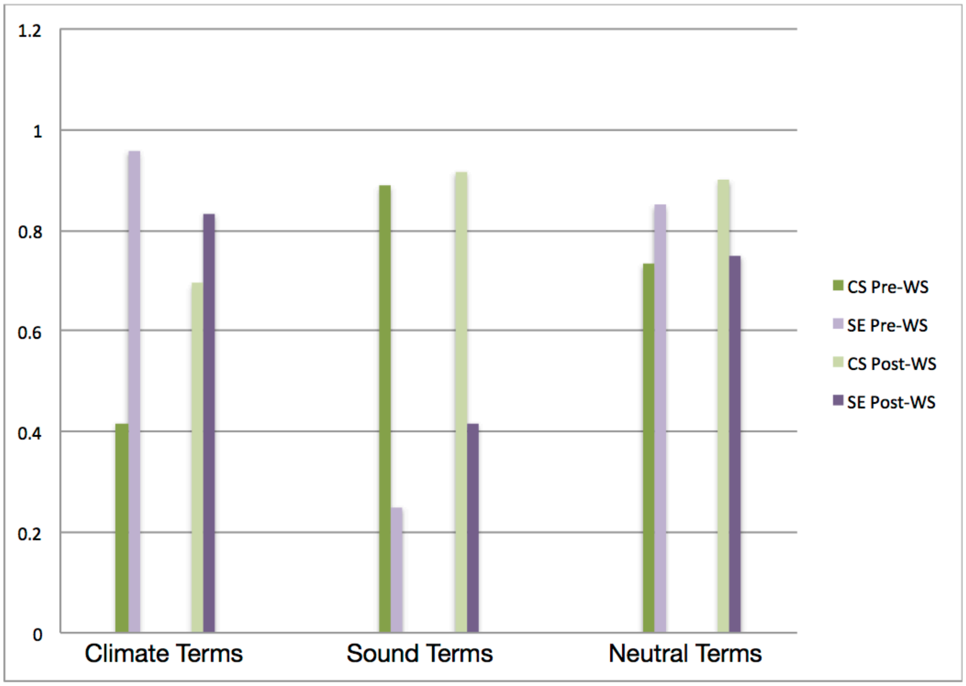

Figure.6.3. Correct Answers of Sound Experts (SE) and Climate Scientists (CS) to Domain Related Terms in Pre and Post Workshop (WS) Questionnaires

6.3. CONTEXTUALIZED COMMUNICATION AND ITERATIONS

Based on feedback from the participants, the collaborative nature of the workshop was very refreshing and innovative. Empowering the users in making design decisions helped to engage them more in the process of sonification and designing sonifications together with sound and sonification experts gave the climate scientists more perspective on how sonification is really done, what are some of the possibilities, and how sound parameters could be used. Sound experts on the other hand gained deeper insights on climate data science and some of the interesting features of climate data that could be interesting to sonify and analyse.

The main issue faced by the participants throughout the workshop was the time pressure. The programmers and sound experts did not get a chance to develop all the ideas discussed in the groups thoroughly. Another challenge was that climate scientists were not very involved in the technical problem solving related to the software platform, which took a huge amount of time. Having more technical preparation together with the programmers beforehand could have saved some time. Reading and handling data in a language new to programmers was very challenging and time consuming in some sessions. Additionally, having a workshop at the early stages of the software development cycle worked as a usability test with expert users. In order to get experts to develop a larger variety of sonifications, regular interactions after the workshop would be necessary to keep them familiar with the system updates and new features and possibilities as the sonification platform evolves.

6.4. CONTEXTUALIZED COMMUNICATION AND ITERATIONS

Overall, the approach to create a pool of sonifications using a framework with a multidisciplinary group is very challenging. The process worked in the sense that we gathered a diverse set of data analysis problems, solutions, and methods that work for climate scientists within our sonification framework.

One of the main challenges that we had throughout the project is the domain scientists' skepticism towards sonification and auditory display as a useful tool. The user's cultural bias is discussed in previous papers of the authors. The multidisciplinary workshop helped to reduce this skepticism because of the hands-on nature of the hack sessions. However, there are still very few convincing examples of sonifications, which demonstrate a great improvement over the existing data analysis methods that climate scientists use. As our future work, we continue to involve and update climate scientists and sonification experts through ongoing workshops, tutorials, and usability tests as the framework and our sonification prototypes improve.

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APPENDIX I

CARRYING THE SONIFICATION FRAMEWORK TO AN ART INSTALLATION

The SysSon platform is also used in the form of an installation. The features that are used in this form were slightly different, therefore I touch the topic briefly here in this Appendix.

The data space observed emerges out of a net that is stretched over the globe and is monitored during a long period of time. How can that complex data space – as it is produced in climate research – be displayed through sounds in a microclimatic exhibition space?

So far, researchers have focused on artificially simulating the development and creating visual representations of this data. Yet, this project wishes to represent that heap of information using another dimension of our senses: hearing. The data collected is translated into sounds, this means the data becomes audible.

The task of the workshop was to create a spatial ambience and a sensorial interface to display the sounds – which resulted from the process described above – and to interact with them. The final installation is presented in an interdisciplinary exhibition in the Forum Stadtpark Graz, aiming to make this particular research perceivable for a broader audience. An immersive spatial setting displays sensors that transform the impulses given by visitors into a modulation of the sound patterns.

CONTENT

Sonification is still a young field with few scientific conventions. Various strategies for sonic translations have been implemented in the installation, based both on evaluations within the research project SysSon and on artistic decisions.

The data used stems from (1) a climate model and (2) from satellite measurements:
(1) Simulations of past and future climates performed with the Earth System Model MPI-ESM-LR (Max-Planck-Institute for Meteorology Hamburg, Deutsches Klimarechenzentrum) for the recent world climate report. A historical run 1850–2005 is combined with future projections 2006–2300 for a midrange concentration pathway (RCP4.5, r1i1p1). These data were post-processed by the Wegener Center for Climate and Global Change, University of Graz. Parameters include temperature (tas), precipitation (pr), wind (east-ward or ua), and radiation balance.
(2) Satellite measurements from GPS radio-occultation processed at the Wegener Center. The derived parameter is temperature anomaly (ta-anom) for the past decade 2001-2012.

The locations within the exhibition space reflect two types of translations. In most cases, data is projected through a derived version of the Dymaxion map, in other cases latitude information is combined with altitude levels of the atmosphere.

An icosahedral unfolding of the earth's spherical surface is an approach that goes back to the architect Buckminster Fuller. This “Dymaxion” projection is the only flat map of the entire surface of the earth which reveals our planet as one island in one ocean, without any visually obvious distortion of the relative sizes of the land areas. This map is utilised both in the sound layer of the system's idle state and in most sonification layers.

When data sets only specify longitudinal means, higher levels of the atmosphere are paired with the given latitudes. Finally, radiation based data is given globally and distributed across all channels using a granular pattern.

SOUND LAYERS IN THE EXHIBIT

The installation is characterised by transitions and cross-modulations between a purely data-driven sonification and the appearance of sounds from field recordings. Seven sonification layers have been developed that make use of different data sets:

id 0 - soundscape:

- This layer corresponds to the idle state of the system and is heard when no sensors have been moved recently. Recordings submitted to the Freesound.org platform were selected based on their geo-tag locations and their ability to coexist with the other sounds, mixing naturally occurring and culturally connoted sounds.

- Sound files with the following ids were used under their respective Creative Commons licenses: 19550, 19992, 28264, 36430, 39895, 51904, 52647, 65495, 67031, 96175, 103115, 103189, 110921, 133832, 138997, 143115, 150865, 152656, 156562, 163607, 163608, 173095, 176028, 176385, 178648, 181364, 186860, 211063, 221859, 222037, 222640, 232411, 233194, 233702, 233704, 234888, 241956, 245826, 249504

id 1 - pitches:

- This layer involves a typical approach to sonification—a temperature parameter is “mapped” to the resonant frequencies of sound grains. Here increasing pitch (high frequencies) denotes decreasing (low) temperature. The coldest part of the earth, the Antarctic, is easily located and perceived through a clanking timbre. Depending on the tempo in which time unfolds, one can also perceive the change in seasons and the opposition of southern and northern hemisphere.

id 2 - density:

- Another standard parameter of climate data is precipitation (rain, snowfall, …) This layer associates the amount of precipitation with the density of sonic grains.

id 3 - anomalies:

- This layer uses measurement data from radiosondes. Temperature anomalies have been calculated and represent the deviation from the mean temperature for each month and location on the earth over many years. Two distinct timbres are chosen to indicate unusually cold and unusually hot months.

id 4 - intensity:

- The soundscape from the idle layer has been processed to have a flat or “greyish” spectrum as well as a steady dynamic envelope. It is then subject to the modulation in intensity by a climate parameter, precipitation. A careful balance is achieved between a “neutral” matter and the possibility to still identify small gestures, such as fragments of voices, within the mass.

id 5 - blops (precipitation clusters):

- More abstract methods of sonification usually involve the post-processing of the given data. Here, a method from image processing, “blob detection”, was applied to generate clusters and trajectories of precipitation events that move in time and space.

id 6 - harmonic field:

- The basis of all periodical changes in climate is the energy of the sun. This layer uses data of the radiation balance, the breakdown of all shares of in-going and out-going radiation to/ from the earth and levels of the atmosphere.

id 7 - wind:

- Wind, as a vectorial entity, is a demanding parameter for any data “display”. From the decomposed vector, we chose the east-ward component. The sounds are based on acoustic wind recordings modulated in their intensity, especially making perceivable the global west-wind zone.

An important aspect of the composition is the interplay of these individual layers. They emanate from the locations in the exhibition space where the sensors are suspended, gradually filling the space. The appearance and disappearance of the layers is a slow process for which the algorithm may choose different temporal and spectral strategies. Many of the interesting sound constellations occur during these transitions and short co-occurrences, emphasising the ephemeral and fragile nature of climate.

APPENDIX II

HOST INSTITUTION: CENTER FOR COMPUTER MUSIC AND ACOUSTICS (CCRMA) AT STANFORD UNIVERSITY

The Stanford Center for Computer Research in Music and Acoustics (CCRMA) is a multi-disciplinary facility where composers and researchers work together using computer-based technology both as an artistic medium and as a research tool. The Stanford University Center for Computer Research in Music and Acoustics (CCRMA), founded by John Chowning, is a multi-discipline facility where composers and researchers work together using computer-based technology both as an artistic medium and as a research tool. CCRMA's director is Chris Chafe. CCRMA's current faculty includes a mix of musicians and engineers including Julius Smith, Jonathan Berger, Max Mathews (emeritus), Ge Wang, Takako Fujioka, Tom Rossing, Jonathan Abel, Marina Bosi, David Berners, Jay Kadis, and Fernando Lopez-Lezcano. Emeritus professor Max Mathews died in 2011.

Besides the amazing facilities and people available at CCRMA, I had the honor of having Professor Jonathan Berger supervising and advising me in my research throughout my stay at CCRMA. Jonathan Berger is a composer and researcher who explores effective ways of using sound to convey information. Berger is the Billie Bennett Achilles Professor in Performance, the William R. and Gretchen B. Kimball University Fellow in Undergraduate Education, Co-Director of the Stanford Institute for Creativity and the Arts (SiCa), and Co-Director of Stanford’s Art Initiative. He is also affiliated with the Center for Computer Research in Music and Acoustics (CCRMA), where he teaches composition and music theory and cognition. He is a composer and researcher, with over 60 publications in a wide range of fields relating to music, science and technology. Research includes studies in music cognition, snal processing and statistical methods for automatic music recognition, classification and transcription, sonification and audio restoration.

Widely used digital sound synthesis techniques like FM synthesis and digital waveguide synthesis were developed CCRMA and licensed to industry partners. The FM synthesis patent brought Stanford $20 million before it expired, making it (in 1994) "the second most lucrative licensing agreement in Stanford's history".

As a guest researcher, I had the opportunity to work mainly with two research groups under the supervision of Professor Jonathan Berger:

- The Music, Computing, and Design group
- Physical Interaction Design for Music

The ***Music, Computing, and Design (MCD)*** research group, led by faculty member Ge Wang, conducts fun, innovative, and impact-producing research in computer music, including in (but not exclusive to) the following areas:

- Design of software systems for computer music (of all types and scales)

- Programming languages and interactive environments (e.g., ChucK, Supercollider)
- The social, cognitive, human aspects of music and computing
- Software interfaces / interaction paradigms for composition, performance, and education
- Music information retrieval
- Computer-mediated performance ensembles (e.g., laptop orchestras; SLOrk)
- Mobile music / social music (e.g., mobile phone orchestras, MoPhO, also see Smule)
- Performances paradigms (e.g., live coding)
- Education at the intersection of computer science and music

Physical Interaction Design for Music

Computers are becoming smaller and advanced sensing technologies are becoming more accessible to musicians. These trends allow musicians to create novel interfaces that promote the development of new music performance, new musical practices, and new art forms in general. Besides studying the practical aspects of prototyping new interfaces, we also research theory for conceiving of new interfaces and classifying them.