SYSTEMATIC PROCEDURE TO DEVELOP SONIFICATIONS

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ABSTRACT

The amount of data to analyse is increasing rapidly, but our ability to understand it remains constant. To gain better understanding of data, fields such as data mining, visualization and sonification are employed. Despite promising progress in auditory research and the potential benefits, we currently see little impact of audio in data analysis interfaces. New contexts of use and inclusive design principles increase the need for an efficient, multi-modal means of conveying information.

Inspired by these needs, this thesis describes the challenge of data sonification and knowledge discovery in general and examines human-computer interaction methods with a focus on sonification as parts of a combined methodology for the exploration, analysis, and representation of complex data. The goal is to enhance knowledge transfer in auditory display design and to enable designers to build more efficient and compelling auditory solutions. As a starting point, the current practice in data analysis tasks by the users is investigated. Building on the results, in order to make the process accessible to users and data scientists, a tool is introduced. Finally, a series of studies and examples show how the methodology and tool can be used to address a range of problems. Experts in auditory display design and climate science participated in the studies to determine the usefulness of the tool. The studies and an interdisciplinary workshop facilitated the transfer of sonification design knowledge and skill between sound experts and domain scientists as well as promoting reflection on human-computer interaction design methods. Furthermore, insights have been gained about the design process which lay the foundations for future research in this field.

Keywords: Sonification, Auditory Display, Participatory Design, User-Centered Design, Human Computer Interaction

DECLARATION

Some ideas which are discussed in this thesis have already appeared in the author's following publications:

Goudarzi, V. *Exploration of sonification design process through an interdisciplinary workshop*, In Proceedings of the Audio Mostly Conference (AM 2016)

Goudarzi, V., Vogt, K., Höldrich, R. *Observations on an interdisciplinary design process using a sonification framework*, In Proceedings of the International Conference in Auditory Display (ICAD 2015)

Goudarzi, V., Rutz, H. Vogt, K *SysSon: A Sonification Platform for Climate Data*, In Proceedings of European Geosciences Union General Assembly (EGU 2014)

Goudarzi, V., Rutz, H. Vogt, K. *User Centered Audio Interface for Climate Science*, In Proceedings of the Interactive Sonification Workshop (ISon 2013)

Goudarzi, V., Vogt, K. *Contextual Inquiry for a Climate Audio Interface*, In Proceedings of the Interfaces and Human Computer Interaction (IHCI 2013)

Vogt, K., Goudarzi, V. ,Parncutt, R. *Evaluating Aesthetics in Sonifications*, In Proceedings of the International Conference on Auditory Display (ICAD 2013)

Goudarzi, V. *SYSSON: A Systematic Procedure to Develop Sonifications*. ACM CHI Extended Abstracts (CHI 2013)

Vogt, K., Goudarzi, V. *Sonification of Climate Data*, In Proceedings of European Geosciences Union General Assembly (EGU 2013).

Vogt, K., Goudarzi, V., Höldrich, R. *Chirping Stars*, In Proceedings of the International Conference on Auditory Display (ICAD 2012)

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1 INTRODUCTION

1.1. MOTIVATION AND AIMS

The goal of this work is to study the use of HCI methods in developing sonification tools. It investigates the current use of HCI design practices and proposes a systematic framework to support designers and users in building on previous work effectively. As a core concept in this framework, it is proposed to use *User Centered Design* and *Participatory Design* to incorporate users in design and communicate sonification design knowledge.

For the implementation of methods and tools the meteorological climate data is used as an exemplar. Climate data is an ideal data domain for a number of reasons including the typically large multivariate data sets, the dynamically changing time-based nature of the data, and the complex nature and process of creating models. The hope is to develop a method in which sonification provides a desired and useful tool for climate scientists and a reproducible process to guide other sonification designers in developing other auditory displays. Furthermore, the timely issue of climate change makes sonification potentially useful and attractive to a wide general audience.

1.2. SCOPE OF THE SYSSON PROJECT

This thesis is initiated and evolved through SysSon (Systematic Procedure to Develop Sonifications)[1] project funded by the Austrian Science Fund (FWF, P24159), which ran from 2012 to 2015. The initial project outline has been described in [VGH12].

1.2.1. Partner institutions

Our cooperation partner in climate research was the Wegener Center for Climate and Global Change at the University of Graz.[2] The Wegener Center is an interdisciplinary research center focusing on "Climate, Environmental, and Global Change". The center includes about 35 researchers, including researchers in the field of Atmospheric Remote Sensing and Climate System (ARSCliSys), in which SysSon project was mostly embedded. This research group stands amongst the leading groups internationally in research on and utilization of Radio Occultation measurements. In a series of experiments, meetings and a workshop, more than 25 staff members took part as participants, many of them consecutively. Expertise of the participants ranged from Master students to professors, while the majority was in a PhD or PostDoc position. At the time of

[1] http://sysson.kug.ac.at

[2] https://wegcenter.uni-graz.at/en/

the studies, the Wegener Center had four different research groups, ranging from economics to physics, with very different scopes and technical frameworks. While in the early stages of the project scientists of all four groups were incorporated, we focused on the climate science for the development and evaluation of the software framework. The main partner from this center was Professor Andrea Steiner. Andrea K. Steiner is in the Wegener Center board of directors and vice head of the ARSCliSys research group. She can build on years of experience in the field of Radio Occultation (RO) and climate with a strong background in atmospheric physics, environmental physics, and data analysis. She contributed to SysSon with her knowledge of RO data and analysis and her experience with data exploration. Her student Martin Jury also contributed in providing model data for the project.

Centre for Systematic Musicology[3] was represented at the early stages of the project for aesthetic evaluation of sound and throughout the project by Professor Richard Parncutt (the head of the institute) as an advisory member of the project. Richard Parncutt is Professor of Systematic Musicology at the University of Graz. His publications address musical structure, music performance, the origins of tonality and of music, and musicological interdisciplinarity. He holds qualifications in music and physics from the University of Melbourne and a Ph.D. from the University of New England, Australia. He is a board member of many leading music psychology journals, founding academic editor of the Journal of Interdisciplinary Music Studies, founder of the series Conference on Interdisciplinary Musicology and director of the Conference on Applied Interculturality Research. R. Parncutt contributed to SysSon with a special seminar on the topic, and with his expertise in aesthetics and listening tests. In course of his seminar, students of this center evaluated sonifications aesthetically with the help of SysSon project members. The results of these studies are published in [VGP13].

Institute of Electronic Music and Acoustics at University of Music and Performing Arts Graz has been the hosting institution coordinating SysSon project, and the source for sound and sonification design, as well as conducting the user studies and *Science by Ear III* workshop.

1.2.2. Project Flow

Different stages of the SysSon project that are investigated and discussed in this thesis include:

- Needs assessments of domain scientists through contextual inquiry and focus groups
- Assessing the sound preference and aesthetics by climate scientists and sound experts
- Usability testing of the tool by climate scientists
- Interdisciplinary workshop for communication between sonification designers and domain experts to create sonification designs.

[3] https://systematische-musikwissenschaft.uni-graz.at/en/zentrum/

- Installation of interactive sonifications for general public
- Usability testing of the sonification tool by sound experts
- Plausibility testing of sonification designs in an online study

1.3. RESEARCH QUESTIONS

We are engaged in design when we create new systems with which people make sonifications to analyse data. When we design a new sonification system we may not have one specific question in mind. In the process of design, our questions emerge with the system we are designing to answer it. Sonification inherits many methods and perspectives from Human-Computer Interaction (HCI). Sonification also takes place within the context of data analysis and we can not separate the design practice from its application. Therefore, design and development of sonification systems take place within practice-based research. Daniel Fallman [Fall03] discusses the relationship between research and design in HCI. We discuss how HCI applies to practice-based sonification and try to understand the nature of our research and the process of systematic sonification. In order to do so, it is essential to study the communication between different domains and explore data analysis workflows in the domain science before and after the use of sonification. The research question strived for by this work can therefore be summarised as:

How to design a systematic approach to develop sonification frameworks that facilitate the efficient use of sonification by domain scientists?

This question can be broken into: how can design knowledge be captured in the particular field of sonification in a systematic manner? Throughout the process of development of a sonification framework, how can the transfer of sonification knowledge to domain scientists who are not familiar with sonification be facilitated? And subsequently, how can domain scientists who are novices in sonification get sufficient guidance to implement sonification design knowledge themselves? Finally, to the benefit of the collaborative approach in the field, how can the experience made in applying the sonification design knowledge be given back into a shared body of knowledge in sonification community to improve and reproduce the existing works. In order to investigate these questions, the following approach has been used:

- Understanding the current data analysis process
- Deriving requirements from current practices used by climate scientists
- Developing methods and processes to sonify climate data
- Integrating the sonification processes in scientists' workflow by involving them throughout the process.

This thesis will investigate which HCI practices should be used in design of sonification frameworks, and what the barriers are that hinder the effective reuse of sonification design knowledge. Building on the results of the early stages of the work, requirements are derived and a systematic design framework is developed that supports sonification designers in creating and communicating sonification design knowledge in the context of climate data. Finally, the last phase aims to put in use this framework and test its usefulness for domain scientists and expert sonification designers in an interdisciplinary process.

1.4. STRUCTURE OF THE THESIS

This work is organised in seven chapters. The first introduces the research questions and specifies the scope and the main objective of the work. Chapter two provides an overview to data mining in general and auditory tools for data analysis in specific. Previous efforts in auditory display design are covered and related topics in the general field of sonification are discussed. Chapter three focuses on the history and current methods of HCI and investigates the methods of the third wave that are more useful for this work. Chapter four reports on studies that led to the design and development of a sonification framework. Chapter five introduces SysSon framework and its components in the first half of the chapter, and reports on usability tests using SysSon framework in the second part of the chapter. A detailed background on participatory design is presented in chapter six. An interdisciplinary workshop and the methodology used in the workshop is laid out in the same chapter. Chapter seven concludes this thesis by reflecting on the work conducted. Appendix I presents an art installation that was a side product of SysSon project to emphasize the social impact of sonification in order to raise awareness on climate issues. Details on studies from different chapters are collected in Appendix II in a chronological order. As a valuable side-product of the evaluation of the studies and workshops, a small collection of sonification designs are presented in Appendix II that could be seen as the source for a larger community effort towards a body of collaboratively developed and shared sonification design knowledge.

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 context 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. Some theoretical framework for common visualization techniques and statistical graphics are discussed and in order to understand sonification properly, a brief 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 auditory perception and how to develop techniques which allow the presentation of data in form of sound. Finally, some sonification frameworks that are used for data analysis tasks and challenges for using them are discussed.

The use of data mining and sonification in the context of a data-intense domain such as climate science is explored as an exemplar. Climate data set used throughout this thesis are described where necessary, the data features used in the examples are outlined in the context of the related chapter. The goal is to improve the climate scientists' knowledge of features and patterns hidden in the data. Climate data is an ideal sonification domain for a number of reasons including the typically large multivariate data sets involved, the dynamically changing nature of the data, and the nature and process of creating models. Climate science data is usually temporal, spatial, or spatiotemporal, making 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 specifically for climate science is that climate data are geographical and inherit spatial or temporal correlation properties. Additional challenges in sonification of climate data stem from 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 recent decades has exposed every field in science and technology to data-rich disciplines. It has enabled the development of methods and tools to analyze huge amount of digital data and extract useful information from its rapidly growing volumes. The rate of data generation and storage far exceeds the rate of data analyses which has the potential to cause loss of scientific insights from the data. Thus, the use of new ways of data mining and knowledge discovery such as machine learning, pattern recognition, information retrieval, visualization, 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, an interdisciplinary subfield of computer science* [FS96], 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 (KD) is the process of identifying viable, novel, useful, and understandable patterns in data. Fig.2.1 illustrates the steps that construct knowledge discovery processes according to Fayyad [FPS96]. Fayyad’s overall process of finding and interpreting patterns from data involves the iterative application of the following steps:

- 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 KD 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 KD 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.

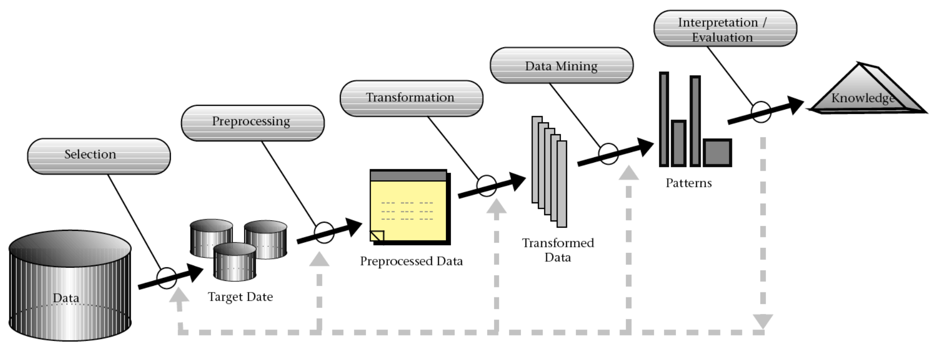


Figure 2.1 Overview of the steps that compose Knowledge discovery process [Fayyad et al. 1996]

The Knowledge Discovery approach is interactive and iterative involving numerous steps with many decisions made by the user. Brachman and Anand [BA96] give a practical view of this process, emphasizing the interactive nature of it. In data analysis it is essential to avoid data dredging– 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 categorized 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.

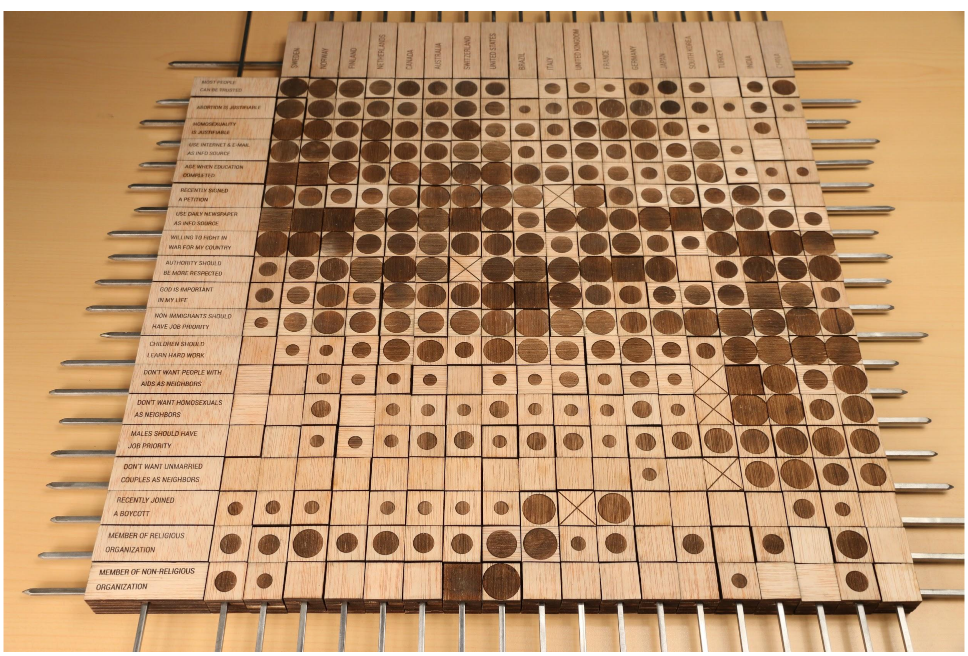


Fig.2.2. A large-scale replica of Jacques Bertin's physical matrices that he called Domino, source: [PLD+15]

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. For Bertin, data analysis starts with a two dimensional matrix where both dimensions are reorderable. Reordering was the most time-consuming part of matrix visualisation in Bertin's process in 1960s with no computer. Therefore, he designed a mechanical device to facilitate the reordering of matrix. Fig.2.2 shows a large-scale wooden replica of this physical matrix that was created for CHI 2015 [PLD+15] participants to try it themselves.

Tufte [Tuf83] is also very influential in using graphics as the main method for analysing and reasoning about data and highlighting 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. [BMG+10] 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, with the embellished version on the left and equivalent plain version on the right.

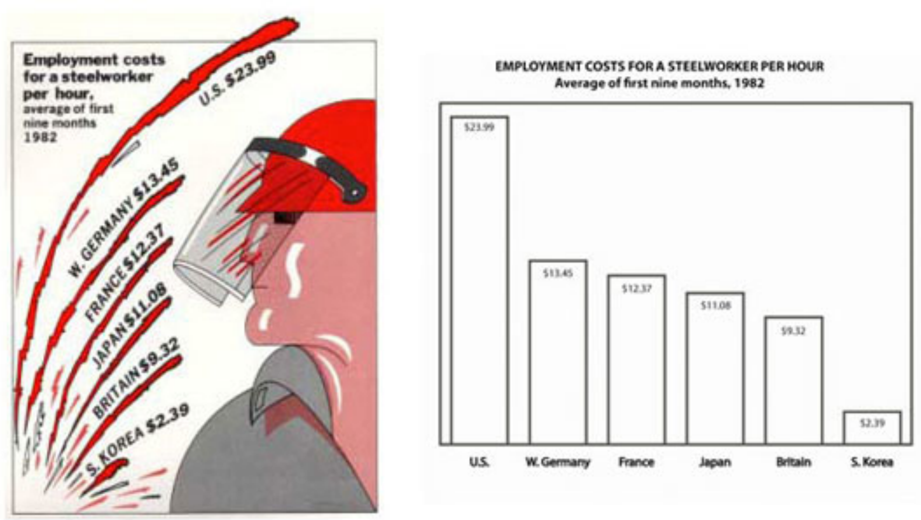
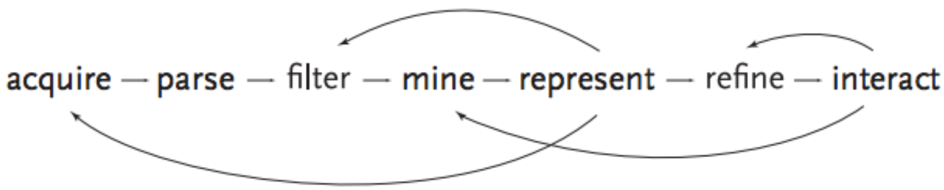


Figure 2.3. Example of embellished vs. plain chart with same data, from Bateman et al.

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 for 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. 3 represents the processing chain of Ben Fry in Computational Information Design.



Computational Design Process, source: [Fry04]

2.2.1. EVOLUTION OF DATA VISUALIZATION

Scientific data analysis is the process of refining potentially large amounts of measured or modelled data into a few simple rules or parameters that 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’ [Tuf83], 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 multivariate datasets, the visualisation by Chernoff faces, Andrew curves, parallel coordinate curves or multivariate glyphs are used [TSS86]. These techniques can be combined in many ways. The most common technique for graphing data is a 2d scatter plot which is also used as a visual representation techniques for: Principal Component Analysis (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 for which they are used. 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.

The science that concerns itself with low-level 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] there 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. The auditory system allows the ability of backgrounding 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 range using auditory displays is possible because of the acute temporal resolution in the hearing sense, which is 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 and this 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 modern 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 a 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 shut down at any time.

In addition to these individual characteristics of each sensory modality, 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, they studied the auditory effects on visual motion perception by 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. For examples, 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 (see following paragraphs) 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 the viewing of 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 a non-speech acoustic signal, 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 systematic, 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.

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 is usually scaled 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 understanding 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 some of their characteristics. The following data sonification tools all have a GUI (Graphical User Interface) and require no programming skills by the data analyst. The data is imported over text or Excel/CSV files as 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 focusses on sonification of space physics data such as Cassini spacecraft crossing the bow shock of Saturn, and on 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 the 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 [Wor09], twitter data sonification [DHW11] and [HNE+12], network data sonification [Wor15] , 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 auditory display methods have been designed and developed without involving the users throughout the design process. The result of such a design process is a tool that doesn't necessarily fulfil the user's needs, could result in poorly designed displays, or remain 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 involves understanding the users and respecting human diversity.

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

- What are the most appropriate HCI methods suitable for designing auditory interfaces?
- How is a User-Centered-Design process adapted to the design of sonification interfaces?
- Given a sonification framework, how can a pool of sonifications be created? Where do these techniques fail and where are they superior to visualisation?
- How to develop some standard sonification techniques, which assist the data mining workflow 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?

3 HUMAN COMPUTER INTERACTION

3.1. INTRODUCTION

The question persists and indeed grows whether the computer will make it easier or harder for human beings to know who they really are, to identify their real problems, to respond more fully to beauty, to place adequate value on life, and to make their world safer than it now is.

Norman Cousins - The Poet and the Computer

What is HCI and design process, and how it could help to improve user experience? Why are so many products, systems, or user interfaces hard to use? Why should we be trained in human computer interaction? This chapter will provide a quick overview in HCI fundamentals such as user experience and interaction design, the evolution of HCI through three paradigms, principles and guidelines in HCI, and finally the practical stages of the design process.

The main challenge in Human Computer Interaction is that people and computers are different. We focus on human-centered view, but many designs derive from a machine-centered (computer-centered) view as their central concept because it is faster and easier for the designer/developer to create such systems but not for the people who are supposed to use the system. Table 3.1. shows human and machine centered views according to Norman [Nor93].

View	People are	Machines are
Machine-centered	Vague Disorganised Emotional Illogical	Precise Orderly Undistractible Unemotional Logical
People-centered	Creative Compliant Attentive to change Resourceful Able to make flexible decisions based on content	Dumb Rigid Insensitive to change Unimaginative Constrained to make consistent decisions

Table 3.1. Machine and people-centered views (Adapted from [Nor93])

Norman also stated that designers have some conception of the system they design which may or may not be the same as what the system actually does. Therefore, designers design a system's image that they intend to reveal their ideas. This image can only be revealed through documentation, interaction, and interfaces. System image created the idea behind Norman's mental models which will be discussed in more details in the next sections. As it is illustrated in Figure 3.1. people interact with the system image and from such an interaction they derive their conception (which is also called "mental model") of what the system is or does.

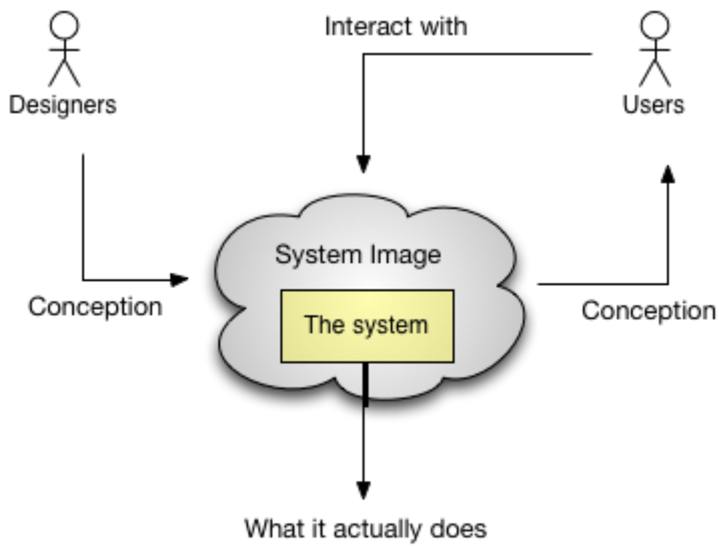


Figure 3.1. The system image

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.*

From the definition above it's evident that ***interdisciplinarity***, ***interaction***, and ***user experience*** are some of the core concepts in HCI which have led to its advancement. Furthermore, Wania et al. [WAM06] categorised the HCI research into seven clusters: Design Theory and Complexity, Design Rationale, Cognitive Theories and Models, Cognitive Engineering, Computer-Supported Cooperative Work, Participatory Design, and User-Centered Design.

Because of its interdisciplinary nature, HCI has grown into an unrestrained domain. In the first decade of its evolution, HCI started with studies in the interactions and the relationships between humans and computers, focused on human factors/engineering, and interfaces (especially on the design criteria for graphical user interfaces or GUIs) to create more usable systems. As interface problems were defined more specifically and understood by a more diverse group of users, the main HCI focus started to move beyond the interface [Fis93]. (As stated by HCI pioneer Douglas Engelbart : *If ease of use was the only valid criterion, people would stick to tricycles and never try bicycles*).

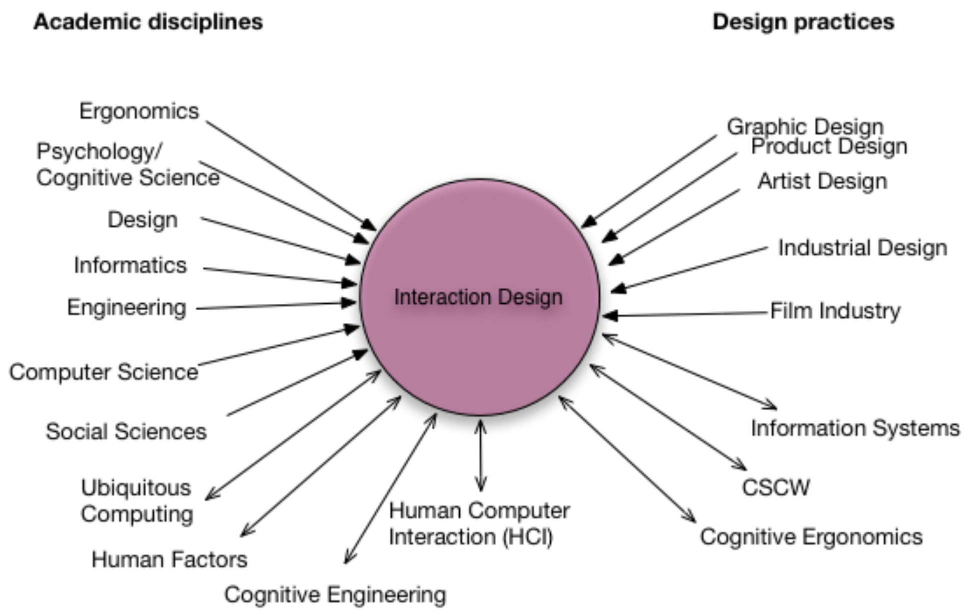


Figure 3.2. Relationship among contributing academic disciplines, design practices, and interdisciplinary fields concerned with interaction design (double-headed arrows mean overlapping)

Another rationale behind evolution and change in direction of HCI is the rapid pace of technological advancements in the last decades(e.g. the internet, wireless technologies, mobile devices, wearables, pervasive technologies, tracking devices) which has led to new ways of user experiences, interactions, and communications. Therefore, design methods from different fields such as ethnography, and cognitive science have been imported to computer science to study the interactions of humans and computers. Additionally these methods have been transformed to adapt to the new interactions between humans and machines. For example, usability is expanded from traditional goals such as efficiency to user experience goals such as aesthetically pleasing, motivating, and fun [RPS02].

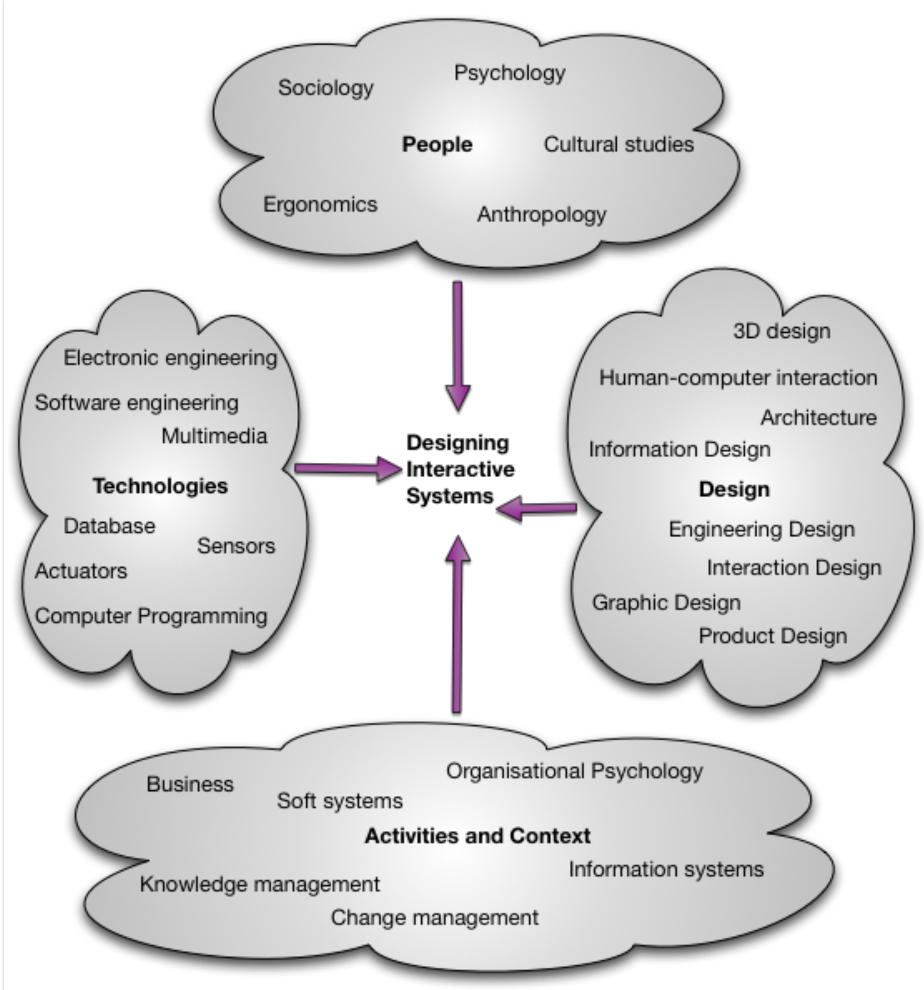


Figure 3.3. Disciplines contributing to interactive system design

The term ***interaction design (ID)*** is also created in the context of HCI to emphasize on what is being done (the interaction) rather than the components it is being done to (the computer, and the human). Rogers et al. define interaction design as: *"the design of interactive products to support people in their everyday and working lives"* [RPS02] and Winograd describes it as: *"designing spaces for human communication and interaction"* [Win97] In early 2000 researchers distinguished ID as a broader domain than HCI and have been expanding the concepts and methodologies of ID till now [PSR15]. Preece et al. stated that ID is more concerned with the theory, research, and practice of designing user experiences for all sorts of technology and systems. Figure 3.2. shows all the disciplines that have the goal of designing systems to match the users' goal, nevertheless, each with a different focus and methodology. Designing interaction and interactive systems needs expertise from a variety of domains. Beynon [BTT05] has summarized contributing disciplines in Figure 3.3. which has many overlaps with Preece's overview.

The international standard on ergonomics of human system interaction, ISO 9241-210 [ISO09] defines user experience as "a person's perceptions and responses that result from the use or anticipated use of a product, system or service". According to the ISO definition, ***user experience(UX)*** includes the users' emotions, beliefs, preferences, perceptions, physical and psychological responses, behaviours and accomplishments that occur before, during and after use. The ISO also list three factors that influence user experience: system, user and the context of use. (Figure 3.4 shows a schematic of user experience(UX) during interaction) User's motivation, resources, mental state, knowledge are some of the attributes that influence user's interaction with the system.

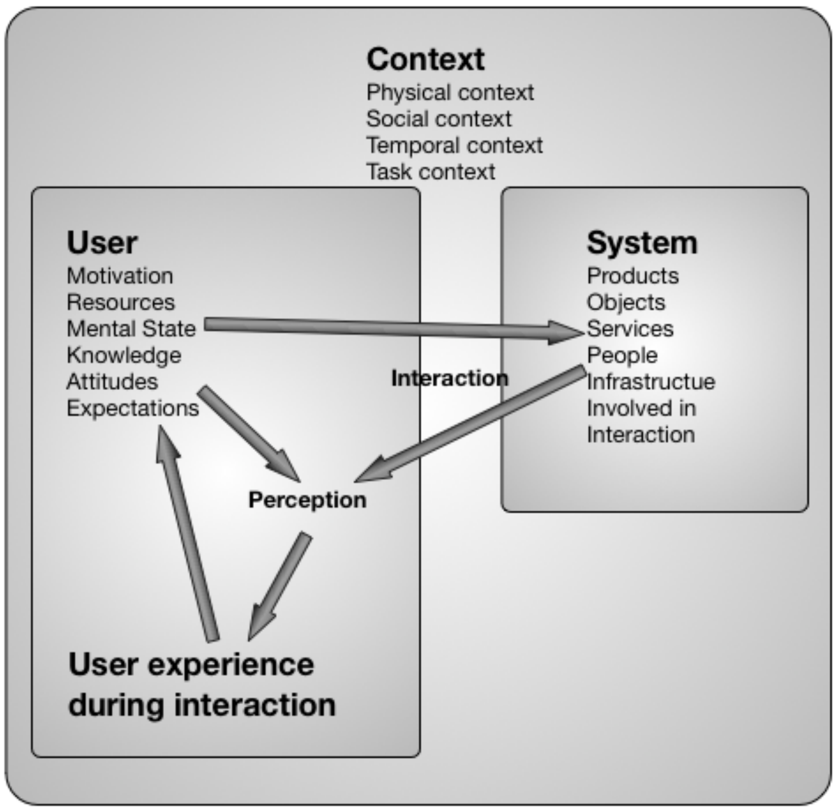


Figure 3.4. User Experience during interaction. (adapted from [BTT05])

Dan Saffer demonstrated that there are many areas of focus in UX(see Figure 3.5.) They share common features such as goals and activities. For example, interviewing is a technique that can be used by a User Researcher and an Interaction Designer. These two groups of people may interview for different reasons but the skill set can be shared by both. The purpose of explaining these disciplines is to emphasise that UX Design includes many things. It is not to constrain who does what and how. However, Boersma categorizes UX disciplines into the following six to set fine lines between these variety of fields: user research, content strategy, information architecture, interaction design, visual design, usability evaluation.

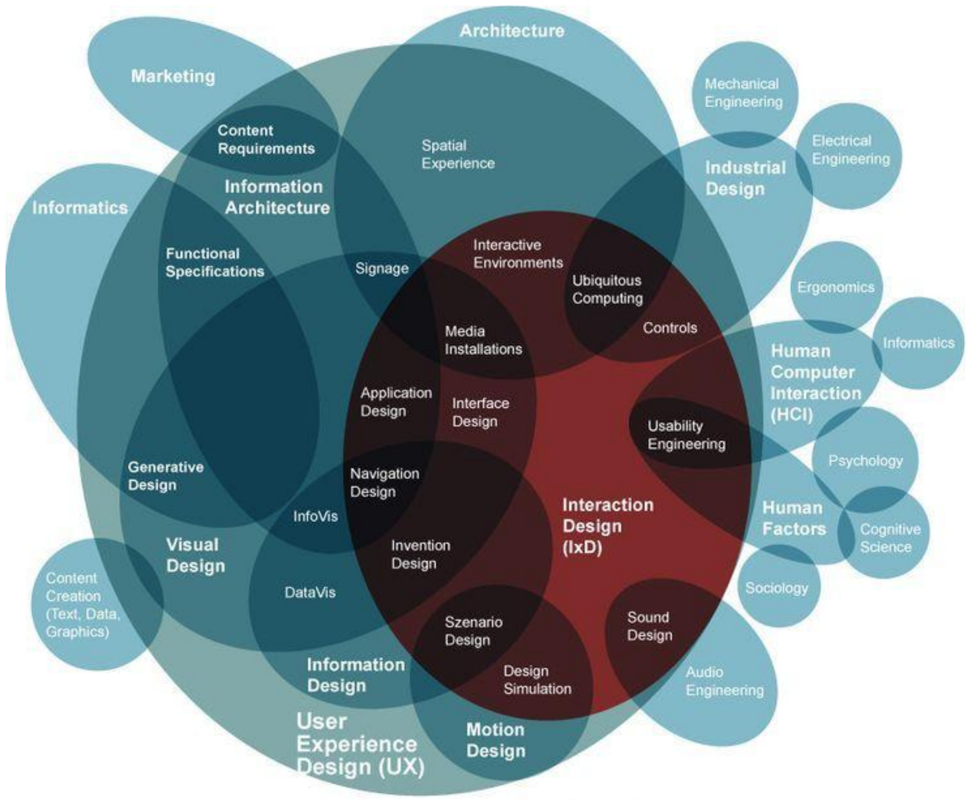


Figure 3.5. The disciplines of User Experience Design [Saf09]

As described earlier rapid technology advancement and interdisciplinarity of HCI has made it a growing discipline. The evolution of HCI is also described as three waves of paradigms in HCI by Harrison et al.[HTS07]; the first being "*Human Factors and Engineering*", the second "*Cognitive Revolution*", and the third "*Situated Perspectives*". Rogers [Rog12] described these three paradigms in form of HCI theories as classical, modern, and contemporary concepts.

3.2. HUMAN FACTORS AND ENGINEERING: FIRST WAVE HCI

The understanding of direct manipulation interfaces is complex. There are a host of virtues and vices. Do not be dismayed by the complexity of the arguments. To our mind, direct manipulation interfaces provide exciting new perspectives on possible modes of interactions with computers... We believe that this direction of work has the potential to deliver important new conceptualizations and a new philosophy of interaction.

Hutchins, Hollan & Norman 1986, pp123-4.

The movement in HCI that started in 1980s is called first wave HCI [Bød06]. It focused on user and user dimensions, and human factors. At that time, the driving factor was limited to desktop computers and the difficulty to learn and use them. Some methods in the first wave include usability testing, experimental psychology, and task based actions. The body of knowledge in this era was contributed from basic research such as psychology and cognitive modeling focusing on users and what they can or can not do with the computers. The main aspects of cognitive psychology that could answer these questions were theories related to human memory, attention, perception, learning, mental models, and decision making. Some of the pioneers of this approach are Norman [Nor98], and Preece et al. [P94]. A common example is the application of the rule that people find it easier to recognize things shown to them than to have to recall them from memory(recognition is better than recall.) This approach has been used since then in most user interfaces to enable the users to recognize items like commands. Another approach at this time was applying theories from basic research. The main advantage of this method was helping research to understand cognitive factors and behaviors by examining human's abilities and limitations when interacting with technologies. A disadvantage of this approach is that we can not simply take theories out of an established field like cognitive science, and apply them to explain other types of phenomena in a different domain (e.g. interacting with computers.) This is because the cognitive knowledge studied in basic research is different from the world of HCI. In basic research behaviors are controlled within the laboratory to examine specific cognitive processes. The cognitions that happen in HCI are not performed in isolation. Therefore, many of the theories adopted from basic cognitive research were not applicable in HCI.

Another approach in the first wave was to model the cognition that is assumed to happen when user performs a task. This approach is heavily affected by cognitive science at the time which focused on modeling people's goals and how they were met. Two of the most common cognitive models were: Hutchins et al.'s [HHN86] conceptual framework of directness , and Norman's [Nor86] theory of action.

The term "direct manipulation" is first used by Shneiderman [Shn83] referring to a class of highly usable and attractive systems of 1980s such as display editors, early desktop office systems, spreadsheets, and video games which allowed the users to interact directly using manual actions rather than typing instructions. The first critiques of direct manipulation was written by Hutchins et al. who tried to explain when and why some graphical interfaces are more usable than their command-line equivalent. Their explanation was abstract and included how the user thinks about the computer's role in the interaction, and how to make the computer do what the user wants. These two aspects (engagement and distance) together were defined to create the directness at the interface:

Directness = Engagement + Distance

In ***conceptual framework of directness,*** Hutchins et al. explain the gap between user's goals and the way a system works in terms of gulfs of execution and evaluation. (Gulfs are the gaps between the user and the interface) The idea of interface Gulfs was that the designers and the users find out how to bridge the gulfs in order to reduce the cognitive efforts required to perform a task. This could be achieved by:

- designing usable interfaces that match the psychological characteristics of the users (e.g. considering memory limitations)
- users learning to create goals, plans and action sequences that fit with the interface's functionality.

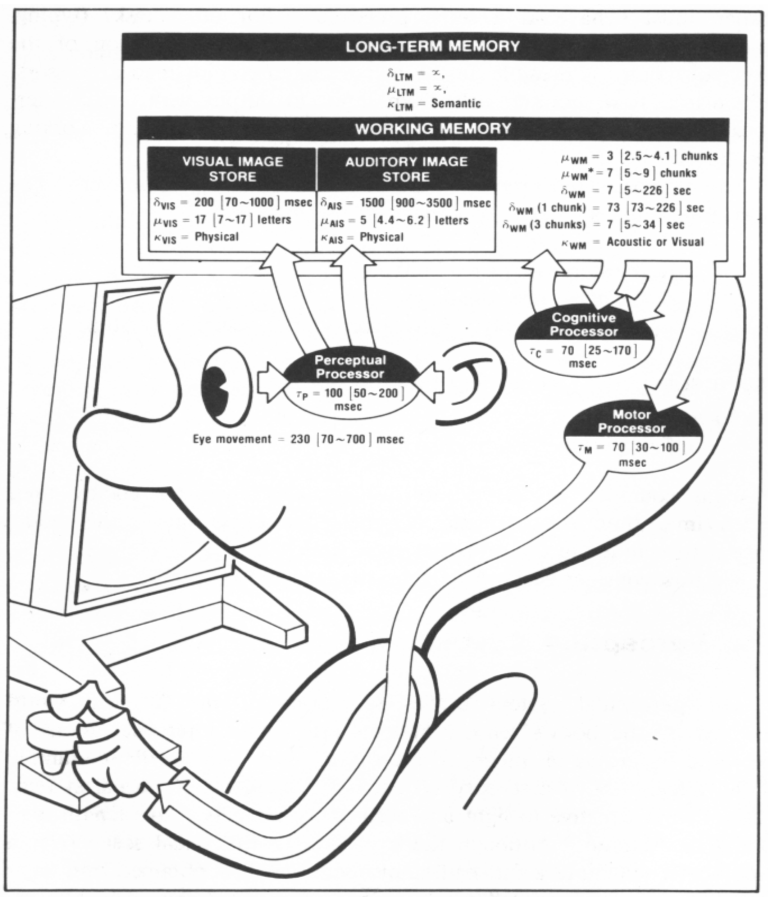


Figure 3.6. The Model Human Processor

Another common cognitive model at the time was Norman's ***theory of action*** that models the assumed mental and physical stages involved in executing actions while using a system. Later, Card et al. [Ca83] created model human processor (MHP), which are cognitive models to make quantitative predictions on user performance. MHP includes three interacting systems: perceptual, cognitive, and motor, each with their own memory and processor (see FIG.3.6). Card et al.

developed predictive models or GOMS (Goals, Operators, Methods, and Selection rules) to evaluate interactive systems. The resulting methods were common tools in usability engineering and HCI in late 80s and early 90s.

A further popular concept during first wave HCI was mental models. Mental models were more appealing because of a more dynamic way of characterizing the knowledge that people have during the interaction with the system. The concept was, the more someone learns about a system and its functions, the more their mental model develops. (for example an engineer of a sound system has a deeper mental model of it than an average user.) The goal of importing mental models to HCI was to predict how good people could rationalize about interactive systems, and by knowing that, providing the necessary training materials that would enable them to learn it effectively. Cognitive modeling made a huge impact on HCI in 80s and early 90s. However, models are simplifications of behaviours and limited in how and what they represent. Although these approximations enabled researchers to model user's problem solving tasks in 80s, they were lacking the context of use and external resources of the usability of the systems.

3.3. COGNITIVE REVOLUTION: SECOND WAVE HCI

Second wave HCI started in 1990s because theories of the first wave were restricted to their scope and could not deal with the real world problems. HCI expanded from research to workspaces and context became where the interaction is happening. Context in many ways has become the focal point of the second wave. Focus moved from the word "Humans" to "Users". Newer methods of cognition, rational thinking, and participatory design became famous. The focus from "modeling in the head" expanded across interactivity, people, technologies, and environment. Rogers[Rog12] outlines the modern approaches in HCI and their origins into:

- Alternative cognitive approaches
    - External cognition
    - Distributed cognition
    - Ecological psychology

- Social approaches
    - Situated action
    - Ethnomethodology and ethnography
    - CSCW theories

- Other imported approaches
    - Activity theory
    - Grounded theory

- Hybrid theories

Only the subcategories that were interesting for this thesis are explained in the next section. For a thorough description of all the above categories refer to Roger's HCI theory. [Rog12]

Distributed cognition was first introduced by Hutchins [Hut95] and describes a cognitive systems which includes interaction among people, the artifacts they use, and the environment where the interaction is happening. He argues that cognition is not an individual system and he applied methods from socio-technical systems. The cognition system could be one person's use of a computational tool, such as a calculator; two people's working on a task together, e.g. two people working on the layout of the same paper sharing the same authoring tool; or wider, e.g. a team of software developers working on the same project using a file sharing system.

Contextual design is an applied approach introduced by Beyer and Holzblatt [BH98] that was developed to collect and interpret ethnographic findings. It was an important component in the development of distributed cognition frameworks. It incorporates the user's context and social interaction into the design and development of software. It's a process of transforming data into a set of abstractions and structures. (This approach is extensively used in the early stages of SysSon project and the related work is described in Chapter 4.)

Ecological psychology was established by Gibson [Gib79] and incorporated into HCI by Bill Gaver [Gav08]. Gibson's perspective was that psychology should study the interaction between humans' perception and action with their environment. Gaver and other HCI experts adapted Gibson's idea into the contextualization of human computer interaction to examine how people interact with technological artefacts. The two concepts of ecological psychology that are most relevant to HCI are ***constraints*** and ***affordance***. Ecological constraints are the constraints and structures in the external world that guide people's actions. Affordances are the relationships between the properties of a person and the perceptual properties of an object within the environment. (E.g. the attributes of objects that allow people to know how to use them or "to give a clue" [Nor88].) In HCI when the affordance of an object is clear it means that it is easy to use. (e.g., door handles afford pulling) The main contribution of ecological psychology in HCI has been articulating specific characteristics about an interface or space in terms of their behaviour, appearance and properties which has led to design concepts in the field of interaction design.

Ethnomethodology and Situated Action were developed as a reaction against mainstream cognitive theories. ***Ethnomethodology*** is originally suggested in sociology by Garfinkel [Gar67] to replace top-down theories to identify invariant structures. In HCI, it is concerned with how people accomplish social order in their everyday interactions. It observes people as they shape their actions rather than the environment shaping their actions. Garfinkel uses the term "social order" which refers to the interactional work through which people conduct themselves in the society. [Gar02] Ethnomethodological approaches in HCI were popularized by British sociologists, who used it to analyze workplace settings such as control center of London Underground or air traffic control. However, Dourish [Dou07] stresses that ethnographic field studies in HCI should go after specific implications for design in order to be relevant.

Activity theory is a conceptual framework originated in sociocultural studies. The foundation of it is "activity", which is understood as purposeful, transformative, and developing interaction between actors ("subjects") and the world ("objects"). It has been introduced by Leontiev and extended by Engeström. [Eng90]. In combination with distributed cognition and phenomenology, it has been used in second wave HCI approaches. The principle of ***object-orientedness*** in activity theory states that all human activities are directed toward their objects and are differentiated from one another by their respective objects. Objects motivate and direct activities, around them activities are coordinated, and in them activities are crystallized when the activities are complete. Analysis of objects is therefore a necessary requirement for understanding human activities, both individual and collective ones. When studying complex real-life phenomena, applying one activity system[4] model is often not sufficient. Such phenomena need to be represented as networks of activity systems. Figure 3.7 illustrates Engeström's triangle: a graphical representation of a human activity system. This triangle shows how key concepts work together or against each other to impact activities. In order to reach an outcome it is necessary to produce certain objects (e.g. experiences, knowledge, and physical products.) Subjects are those individuals who are brought together to work on the same activity by potentially seeing and sharing the same object, an aspect of the social world that draws them in and motivates them. Human activity is mediated by instruments (e.g. tools used, documents, etc.) Activity is also mediated by an organization or community. Also, the community may impose rules that affect activity. The subject works as part of the community to achieve the object. Their work together is governed by a division of labour – or the way in which the work is divided up and who gets to do which bit of it. Rules suggests that there are norms which influence how the members of the community get their labour divided up.

[4] An activity system is not just a user or actor; it includes teams and organizations, it includes culture and mediation of human activity.

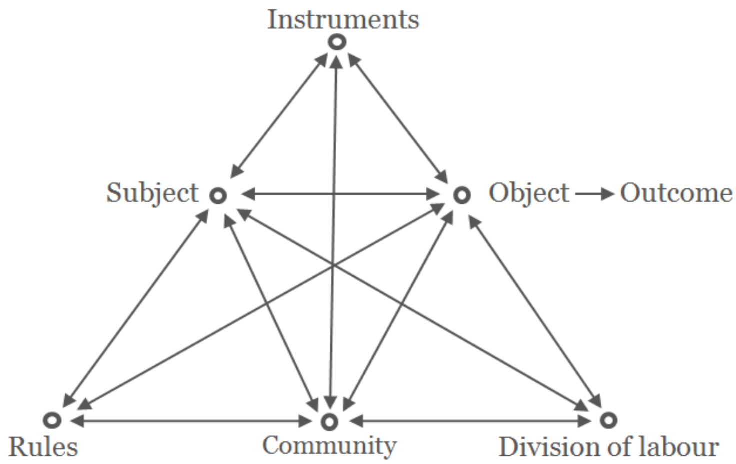


Figure 3.7. The Engeström's triangles of activity theory

Grounded theory is a qualitative approach to help researchers develop theory from the systematic analysis of empirical data. (the theory derived is grounded in data) It was originally developed by Glaser and Strauss [GS67] and has been adopted in different fields. The process of grounded theory requires the researcher to switch between data collection and data analysis iteratively. Data collection is driven by the emerging theory and finishes when no further insights could be gathered from the alternation. The main goal is to define dimensions of relevant categories in data and use those as basis to construct theories of interaction. Glaser and Strauss suggested three ways of coding the data:

- Open coding where categories, their properties, and dimensions are discovered in the data.
- Axial coding where the categories are systematically elaborated and related to their subcategories.
- Selective coding where categories are refined to form a larger theoretical scheme.

Grounded theory has been widely used in HCI especially in interaction design to answer specific question and design concerns. The process of iterating between data collection and coding, creates new theoretical framework to match patterns found in the collected data against an existing set of concepts.

3.4. SITUATED PERSPECTIVES: THIRD WAVE HCI

Third wave HCI started in mid 2000 and expanded the reach of HCI to homes and everyday culture. In this paradigm, the use context and application types are broadened, users are called actors and participants, cultural differences are notable, and thinking out of the box is supported. Anderson [And94] studied the value of ethnography for design and he pointed out that the core of the paradox is that "to understand what any individual item or part means, you have to see it against the backdrop of the whole." This idea links to the observations by Harrison et al. [HTS07] that the *artifact* and its *context* are mutually defining within the third paradigm.

This paradigm should answer questions such as: what should the participants do and what their respective social responsibilities are in a technically vibrant world. Encompassing a new stage of conceptual analysis or "understanding" of human values is the answer of the third wave to these questions. "Being Human" report [HRR+08] extended the iterative model of user centered design by adding "understand" into the four stages (see Fig.3.8). This stage is dependent on the values of interest of the users and can be drawn from different disciplines such as philosophy, psychology, art, sociology, cultural studies, and architecture.

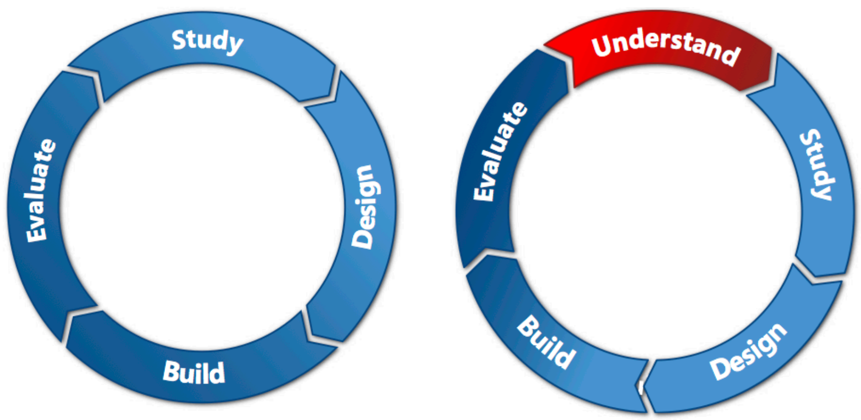


Figure 3.8. The conventional user-centered research and design process (left) and the extended five stage research and design process (right)

Context has been a central point in the second wave and it has been talked about in many ways but it has still been very vague. Engeström's triangle was very often used to describe the dimensions of context. However, there seem to be another new dimension in context all the time and an attempt to make a complete analysis of context in the second wave has failed. Other approaches tried to define the notion of boundary object. The attempts have been to create objects and artefacts that are self-contained to travel across contexts of use. This way of thinking can only resonate with design of mobile technologies as the individual user has access to all her personal documents and can work independently of the place. Bødker described the main challenge that led to the third wave in involvement of the users. People need to be involved in design, not only as workers but as someone who brings the whole life experience with. However, there are many open questions on how to support users during the process of design in use. Fischer explored the domain of how system design could be modifiable to enable the users design in use. His early works [Fis94] focused on designing knowledge- based environments in which users can create, reflect, and shape the systems. Furthermore, he introduced a participatory design (co-design) process between environment developers and domain designers. In his more recent works [FG06], he addressed the challenges of participatory design methods and introduced the evolution of user-centered development towards meta-design (participatory design and it's use is explained rigorously in chapter 6). Improvements in user participation had huge influence on the creation of the third wave. The innovation is user-driven and not task oriented. The cognition is expanded towards exploratory approach where designers seek inspiration from use. To sum up, designing according to the third paradigm is a situated and constructive activity of *meaning making*, rather than *problem solving*.

The third paradigm has become more apparent because of several reasons including:

- the dynamic character of use contexts (the focus moved from workplace to everyday lives)
- issues related to the sociality and situatedness of interaction;
- new ways of learning environments;
- non-task-oriented computing (such as ambient interfaces and experience centered design);
- the role of emotion in human-computer interaction. [HTS07]

3.5. DESIGN TIME AND USE TIME

One of the core issues of system design process is: how do we design and develop systems for many users (at design time), while making it work as if it were designed for each individual user (who is known only at use time)? (see Fig. 3.9) At design time, developers (with or without user involvement) create systems and tools, and they have to make decisions for users, contexts, and for tasks that they can only anticipate. In first wave HCI at use time, users use the system but their needs, intents, and contexts can only be predicted at design time, thus, the system often requires modification to adapt to the user's needs. An issue that can create a challenge might be that use time and design time get blurred. If the system is constantly adapting or is being adapted to the users, use time becomes a different kind of design time [HK91].

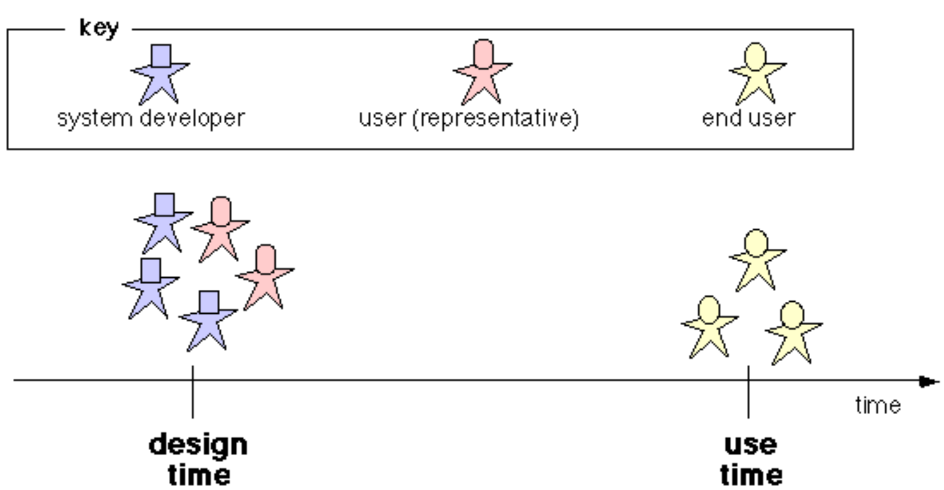


Figure 3.9. Design and Use Time

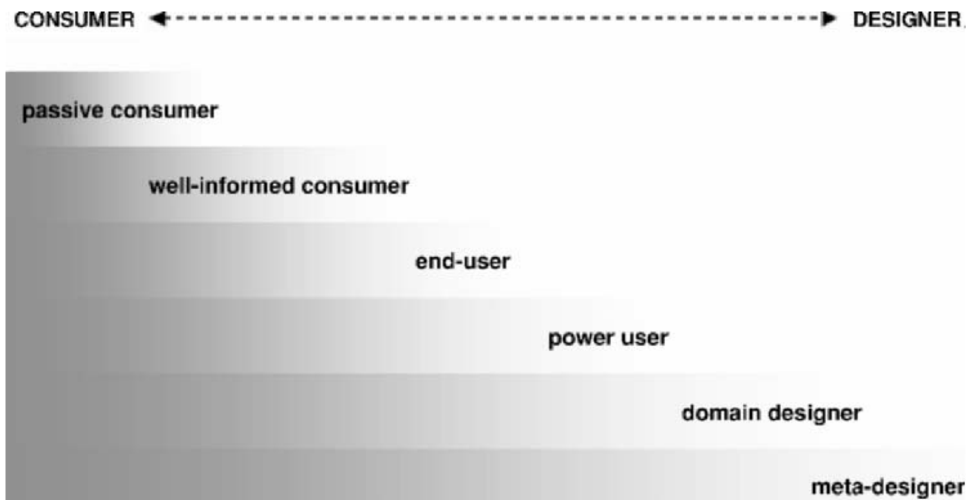


Figure 3.10. Beyond binary choices—the consumer/designer spectrum [FG06]

Brand introduced the concept of underdesign [Bra95] to accommodate unexpected issues at use time. Under-design in this context does not mean less work for the designers and developers, but it is: not creating complete systems at design time. The main challenge of underdesign is in developing not solutions, but environments that allow the users (owners of problems) [Fis94] to create the solutions themselves at *use-time*. As shown in Figure 3.10, Fischer and Giccardo do not assume that being a consumer or a designer is a binary choice for the user: it is rather a continuum varying from passive consumer(user), to well-informed consumer(user), to end-user, to power users, to domain designer[FG06]. Additionally, the same person could be a consumer(user) in some situations and in others a designer; therefore “consumer/ designer” is not a characteristic of a person, but a role assumed in a specific context.

In summary, third wave supports a wide range of different users guides to high-functionality applications with all related possibilities and challenges. A practical design strategy to support users in their own domain of knowledge is that system designers make assumptions about categories of users and sets of tasks in which they want to engage.

3.6. DESIGN PRINCIPLES AND GUIDELINES

HCI design process is a goal-oriented problem solving activity [Jon92] that aims designing interactions with maximum 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 system (what expectations does it create for subsequent interactions?) [Kun10] Throughout the design process the following three components are taken into account:

- Principles of usability for general understanding
- Standards and guidelines to direct the design process
- Design patterns to capture and reuse design knowledge (patterns are discussed in section 4.2)

Dix describes ***HCI design principles*** as widely applicable and general rules with low authority. [Dix09] (e.g. reduce cognitive load in interface design, or interface should be easy to navigate.)

Principles are intended to be general and when they are interpreted for a specific design, they become ***design guideline***. Guidelines [SM86] are more specific, incomplete, and hard to apply. (e.g. always issue a warning before the user deletes a file, or use color RGB #1010D0 on home links)

Standards are guidelines with high level of authority. Usually standards must be applied to a design and may be legally enforced. It has to be defined when a standard has to be applied.

Some collections of HCI guidelines and principles which are described in chapter 4 include:

- Norman's 7 principles [Nor86]
- Nielsen's 10 Heuristics [Nie94a]
- Schneiderman's 8 Golden Rules [Sch92]

3.6. USABILITY AND LIFE CYCLE MODELS

Usability is the ultimate test of a designed system based on measurements of user experience (or requirements analysis) . Requirement is something the product or system has to do or a quality that it must have. (e.g. functional requirements include what the system should do? and a non-functional one is the memory size or what kind of data need to be stored). Some common challenges with usability are that: Usability specification requires level of detail that may not be possible to gather early in design and satisfying a usability specification does not necessarily satisfy usability.

Understanding requirements includes observing and analysing similar systems and discussing the needs of the users to uncover the problems with current designs. Developing may include creating a variety of prototypes and representations of the system until a suitable one is produced. The four basic activities of HCI design process are:

1. Identifying users' needs and establishing requirements
2. Developing alternative designs and building prototypes of the designs
3. Evaluating designs

Understanding these stages is the first step in the design process, but it is also important to understand how they are related to one another in the whole process. The term ***lifecycle model*** is used to represent a model that captures a set of activities and their relations. It is adapted from software engineering [Roy70] into HCI design process where the goal is similar in organizing processes for development of a system. However, the traditional software engineering took a very different approach in that it treated each phase of the software development as an independent entity, which must be completely finished and tested before moving onto the next phase. E.g. in waterfall model which is basically a linear model in which each step needs to be completed before the next one begins. (see Fig. 3.11) The main problem with such an approach is that in practice requirements change over time and the development stages overlap and feed information to each other. The software process is not a strictly linear model but includes a sequence of iterations of activities.

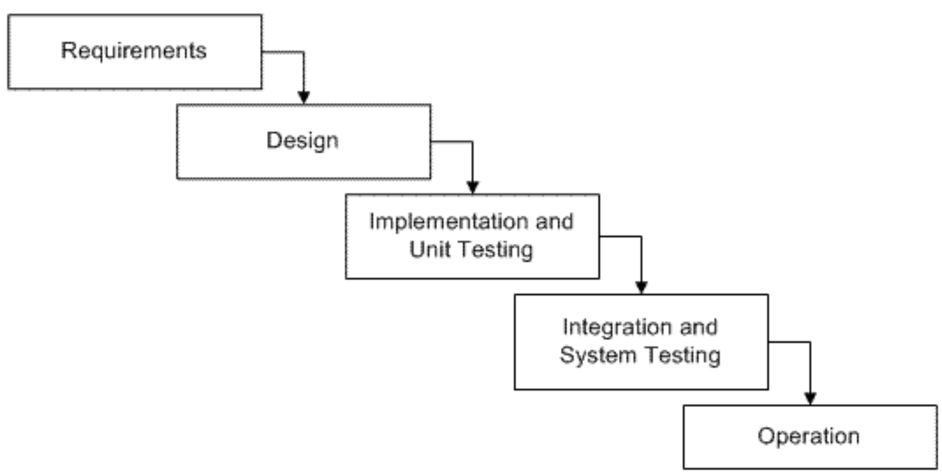


Figure 3.11. Waterfall lifecycle model of software development.

Stone et al. [SJW+05] describe the difference between the classical life cycle and HCI design process in that HCI process is based on the involvement of the users throughout the lifecycle and therefore highly iterative. This distinction is first introduced by Hartson and Hix [HH89] by creating star life cycle. (Fig. 3.12)

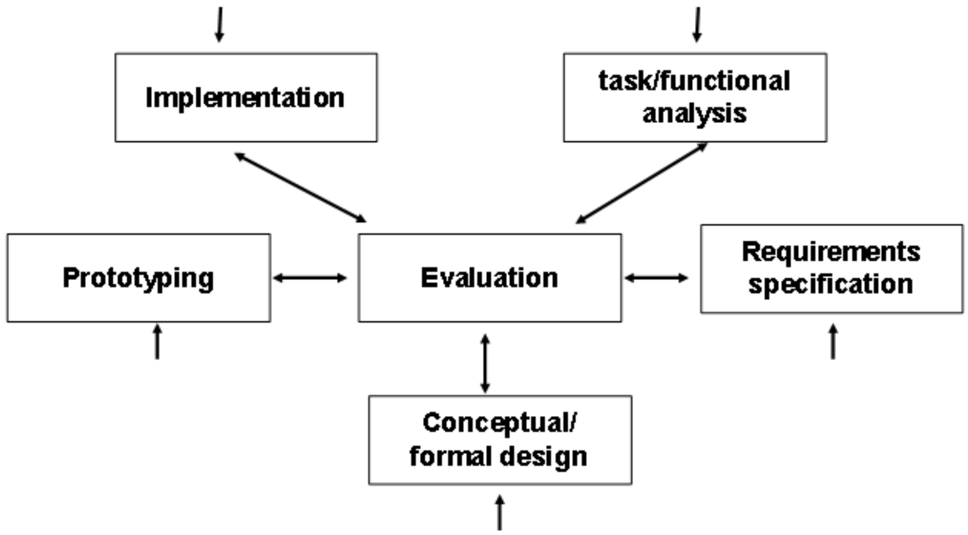


Figure 3.12. Star life cycle model (adapted from [HH89])

The main features of Star lifecycle are:

- Evaluation is at the center of all activities that ensures the final system meets the prescribed usability.
- It supports refinement and rapid prototyping.
- The activities are in no particular order. Development may start in any one of them.
- This model is derived from empirical studies of interface designers.

The International Standardization Organization (ISO) has developed several standards, one of which is ISO 13407: 1999- Human Centered Design Processes for Interactive Systems [ISO09] mainly referring to qualities of the process of developing an artefact. This standard names similar stages and requires that the overall process iterates these stages so many times until the interactive system has reached the required quality. These individual stages are: the identification of the need for human-centered design; the understanding and specification of the context of use; the specification of the user and organizational requirements; the production of the design solutions; and the evaluation of the design against the requirements. (Fig.3.13)

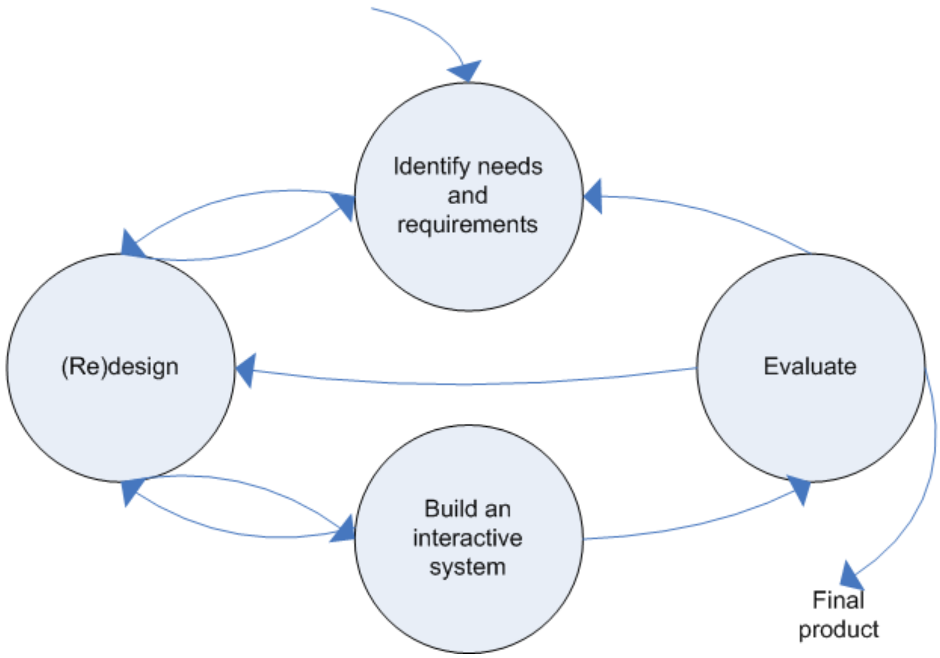


Figure 3.13. HCI life cycle model (adapted from [ISO09])

Overall in both software engineering and in HCI there are process models that include multiple stages from analysis to design to implementation to evaluation with iterations in between and within individual steps.

3.7. DISCUSSION

In this chapter we introduced what HCI as a design oriented field is and how it has evolved within three waves or paradigms. We discussed what these three waves are. The first one focusing on interaction between human and computer as a diode, the second paradigm centered around cognitive factors and finally how the third and last one emerges user experience as the key concept. The third wave (or situated action) has lead to exciting perspectives and difficult challenges. The conceptual shift to a more emotional view of HCI has been accompanied by the development of numerous methods and tools for the design and evaluation of interactive software systems. Some UX related factors in software design such as design time, use time, design principles and guidelines has thus been introduced briefly.

The next three chapters are practical contributions to some of these theories and methods of HCI discussed in this chapter. After explaining each method, we explore how to incorporate the third wave paradigms in auditory display design or as Barrass[5] calls it; Sonic Information Design.

[5] Keynote at ICAD 2015 conference, International Conference on Auditory Display, July 8 - 10.

4 REQUIREMENT ANALYSIS: PRE DESIGN

4.1. USER CENTERED DESIGN APPROACH

People ignore design that ignores people.

Frank Chimero - The Shape of Design

User Centered Design (UCD) means that the designed systems are balanced between user goals, designer's intentions, and technical capabilities. In UCD the goal is to determine how users work, how they think, and how they live. In UCD ***end users***[6] influence how a design takes shape. Design methodologies, such as UCD and participatory design (PD[7]), 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 finalized and employed, modifications are not supported. Designing interactive software systems without enough knowledge about its users could leave them frustrated and unable to complete a task while using the system. Cross and Norman, consider 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 also been cited as a core value to UCD [Nor86]. Patnaik and Becker [PB99] emphasize 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 a 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
4. Functional analysis

Some also commented that design cannot be comprehended as problem solving [Sto92]; or is a richer concept than problem solving [WBDH95].

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[6] End user is the ultimate human user of the system according to Nardi [Nar93]. The term is used to distinguish between those who only use the software and those who are involved in development. Some software products provide services to other systems and have no direct end users.

[7] PD in the context of this thesis is discussed utterly in chapter 6.

UCD is an extensive term to describe how users form and influence the design processes. Norman introduced it in 1980s and the publication of the book; User-Centred System Design: New perspectives on Human Computer Interaction [Nor86] made it widely available. 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[8] 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. (In our context, we try to make it hearable)
- 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 system 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 learning effort. Furthermore, Norman suggests accompanying products by a fact sheet that can be read very quickly and utilises the user's knowledge.

Norman emphasized the importance of fully exploring the needs of the users in terms of the use of the system and to involve them in their actual environment[9] 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 approach for UCD 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 to 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

[8] For more details on design time, check out the previous chapter in section 3.4. Design time and use time.
[9] User’s actual environment or context is explored utterly in the second wave of HCI in section 3.3.

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 system. The involvement of the users assures that the system 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 fulfillment and smoother integration of the product into the user's environment [RSP11]. 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. Another 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 users by empowering them to create and contribute their own objectives in the design process. [10]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. PD [MK93] also involve users in the co-design process with the designers but despite the advantages of PD 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 in contributing and modifying 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 some aspects of Auditory Interface Design and Development is necessary to get a deeper understanding of the core concepts.

Frauenberger describes the history of sound in technology and the use of it in the very first personal computers [FrSt09]. He argues that the gaming industry is the main incentive behind the development and improvement of sound in computers. Furthermore, he distinguishes between "Auditory Display" and "Auditory (user) Interface". The former includes any use of auditory means to

[10] Chapter 6.1. Shows how it's expanded in an interdisciplinary project such as SysSon.

convey information, which is equivalent to the definition of sonification by Kramer as “the use of non-speech audio to convey information” [KWB+10]. “Auditory Display” covers the auditory representation of data as well as the use of sound in user interfaces. "Auditory (user) Interface" is described as a sonically 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 users in the context of the system's functionality and the tasks that they are involved with are the key constituents for a successful design process, especially in an Auditory Display. The concept of task-oriented and data-sensitive auditory information design method (TaDa!) was developed by Barrass [Bar96] as the first step for auditory information design. TaDa starts from a description of a use case scenario, and an analysis of the user's task, and the characteristics of the data. This analysis informs the specification of the information requirements of the sonification. TaDa! includes some key aspects of requirement analysis in general, and yields a structured way of finding the link between information requirements of a task and the information representation used to achieve the designer’s goals. But the resulting sonification does not support user interaction with the information. Additionally Barrass explored an extension of design [Bar03] by introducing design patterns into the sonification field. Design patterns were first introduced in the field of Architecture by Alexander [FrSt09] 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 analyzing 23 proceedings of ICAD (International Community for Auditory Display) conferences on the basis of four themes: design process, guidance, rationale, and evaluation. He describes that all papers introduce the application domain, but contextual information did not play a role in the design process. After the in-depth study 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 [FrSt09] show that the design process for auditory display is mostly unstructured and it provides limited support for the 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). CWA 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:

1. *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. For example, 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.
2. *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. For example, it gives information about which tasks are better suited to be displayed visually and which tasks are more appropriate for auditory display.
3. *Semantic Mapping* provides information about criteria for choosing interface elements so that goal related task invariants are mapped into perceptual properties of the interface. For example, 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 they have been commonly utilized in visual display design. Gaver used ecological concepts in his work on auditory icons and earcons and his 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-steam power plant but they did not use a full EID analysis. Instead they emphasized 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. Based on knowledge of auditory attention, this phase provides requirements on how an auditory display should control attention alongside other interface elements.

4.3. RESEARCH PROCESS AND DATA COLLECTION IN SYSSON

Within SysSon approach, several studies were suited to 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 methodologies were 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[11] [Sch00]. The main objective of this methodology was to gain meaning from scientists' experiences [BB98]. An hour of individual data analysis work (contextual inquiry), an hour of observed team meeting (focus groups), and an hour-long listening test to gather information on user's sound preferences were analyzed. The listening test was conducted at a later stages of the studies and the participants were not all the same as the ones who participated in the contextual inquiry and focus groups studies. Data sources included:

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

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 preferences of 8 climate scientists and 8 sound experts were evaluated.

[11] Reductionism is the belief that human behavior can be explained by breaking it down into smaller component parts.

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 analyze their activities, workflows, and the environmental factors while analyzing data. For the individual interviews, a questionnaire was prepared for the interviewer and observer, both of whom 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. The participant's personal background and qualifications were then assessed to be analysed. 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 of the questionnaire was on exploring the user goals of the scientists. Basic types of performance metrics were gathered from open questions such as:

- Is mainly the task-success that users are interested in?
- How quickly can users perform a task?
- How efficient are they?
- How are errors found during the process (for example 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.

We gathered 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.

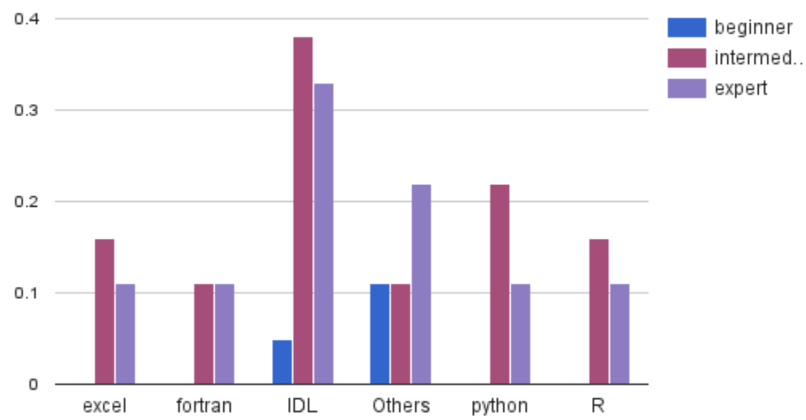

Figure 4.1. Software used by climate scientists

An overview of different software tools that the climate scientists use for data analysis and visualization is shown in Figure 4.1, including their own assessment of their expertise (beginner, intermediate or expert). Interactive Data Language (IDL) 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 were not 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.

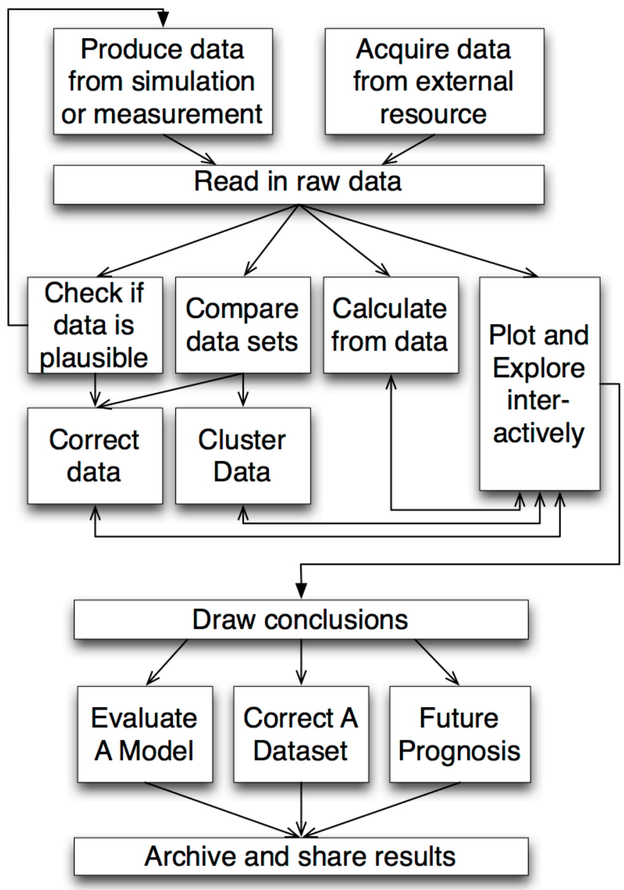

Figure 4.2. Workflow Schemata of Climate Scientists

Figure 4.2, above, shows a common workflow summarizing the data analysis process in all three user groups. The task of analyzing data 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 key parts of the workflow. 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 analyzed 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 focus of the 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 total number of words each person used.)

Furthermore, the words used by the scientists were grouped. The categories for the groups were determined iteratively, where final categories emerged while trying to group the data as far as possible. As shown in Figure 4.3, the top four mentioned 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 were 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 were important, including data acquisition, listing, simple calculations, calibration, and transformation of grids, sorting, and retrieval. 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 when comparing datasets.

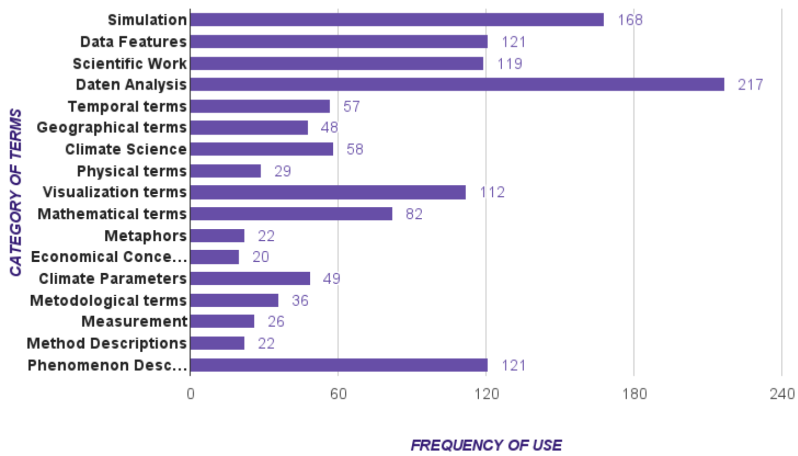

Figure 4.3. Categories of words used by the Climate Scientists

4.3.3. METAPHOR ANALYSIS

Metaphoric sonification is an attempt to create auditory metaphors that relate to the data the sound is originated from. In order to design our sonic display, we decided to explore if there are any specific metaphors in the climate domain; at least not to contradict with them when creating sounds. Therefore, we analyzed the collected words from contextual inquiry and focus groups conversations to hear how the climate scientists communicate between themselves and how they communicate their data to scientists from other research groups. In general, we found few metaphoric terms in the collected words. The participants used the standard science vocabulary, which are not metaphors per se, but they become metaphoric when carried out to the auditory domain. In the following paragraph, the highlighted words are the specific terms that could become metaphoric when used in the auditory domain.

Climate data is ***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 another essential topic in climate science when comparing different datasets or trying to find phenomena at a certain range; resolution in audio could be given by the sampling rate and bit depth. ***Missing data*** plays a large role in climate science; an obvious analogy is making it audible as silent pauses that can be used for a quick scanning of a dataset. An ***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 dynamic 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 timbres. Climate scientists who work with measurement data or with simulation data know about the signal-to-***noise*** ratio. One participant called the atmosphere noisy when 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.

Discussing and brainstorming with the climate scientists, we came up with a few mapping strategies. Some common ones include mapping height dimension in climate data (altitude) to pitch; the geographical spread can be used for spatial rendering in audio. Some weather related phenomena are linked to typical sounds and these 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, in any event, the control of the audio interface will involve actions that climate scientists are used to, such as calibrating or filtering data or sound.

4.3.4. USER STUDY ON SOUND PREFERENCE

In a set of studies sixteen participants from two groups (8 Climate Scientists and 8 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* [Sch93] 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 sonifications, 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. Studies have shown that natural sounds are more easily recognized in an office environment than artificial tones [MBW+98]. Mauney and Walker [MW04] found these soundscapes useful for sonification as they can be easily distinguished from the background sounds but can also fade out of attention, and not be tiring or intrusive when not desired [VLDF14]. Some recent examples include Hermann et al. real-time sonification of Twitter streams [HNE+12], and Boren et al, who use ambisonic sound recordings from urban soundscapes as a layer in an auditory display[BMGR14].

For this study, 24 sound samples, each of 10 seconds duration, were used. All sound samples were chosen by the author to support natural acoustic soundscapes especially climate-related sounds. They were chosen from the 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 could be used to elucidate whether the climate scientists would be able to associate these sounds to parameters of their domain, and whether this association was unanimous. Each study was divided into two sections; the purpose of the first stage was mainly to evaluate the sound samples (stimuli) aesthetically while the second part was used in mapping the stimuli to the climate parameters. The total time for each experiment was between 35 and 45 minutes. All participants[12] were given identical settings, listening to the stimuli via the same type of headphones. They were presented with eight groups of three stimuli. After listening to each group of each three in a dissimilarity rating, they were asked 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 in a random order. They were given 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. (Table 4.1. Illustrates the sounds descriptions) Each sound stimulus was approximately 10 seconds and there was a 10 seconds break between successive stimuli to give the participant time for evaluation or mapping.

Hypothesized climate parameter	Sound description
Temperature	1. Boiling bubble 2. Electric water boiler 3. Pressure cooker
Precipitation	1. Tap water 2. Ocean 3. Heavy rain
Air Humidity	1. Heavy rain 2. Light rain 3. Fog horn

[12] Anecdotally no scientist reported any hearing loss that they felt would impair their ability to make the distinctions required for the studies in which they were involved.

Pressure	1. Water pressure 2. Compressor 3. Steps on snow
Geopotential Height	1. Earthquake rock fall 2. Huge rocks fall 3. Synthetic fall
Refractivity	1. Synthesized crystals 2. Synthesized drone 3. Human coloring refractions on paper
Radiation	1. Geiger counter 2. Radiation beam 3. Abstract geiger counter
Wind	1. Tree leaves rustling 2. Vent wind 3. Wind and rain

Table 4.1. Description of sound samples used in the study. Each group of three (right column) is related to one climate parameter (left column).

In order to compare the effect of auditory experience and music knowledge on evaluating the aesthetics of sounds, the study was repeated with 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. This study showed that not all eight parameters provided perceived links to the sound samples. Especially challenging were the parameters that are more abstract such as temperature, refractivity, and geopotential height. The results for non-abstract parameters such as wind were very clear over both stages of the study and over both participant groups. As a result, we decided to use sounds in the sonification tool (which would be explained in the next chapter) that satisfy either one of these criteria:

1. A sound was mapped to the same parameter by both groups of participants.
2. A sound was rated highest by both groups, and mapped to the hypothesised parameter.

4.4. DISCUSSION

This chapter discussed the current practice in UCD in general and for auditory display design in specific. In the third wave of HCI, the emergence of UCD as a key concept has opened up both exciting perspectives and tremendous challenges. The conceptual shift to a more comprehensive and emotional view of human-computer interactions has been accompanied by the development of numerous methods and tools for the design and evaluation of interactive systems especially in the young field of Auditory Display. User centered research has thus been mainly evolved by novelty and innovation and a majority of the developed tools lack consolidation and reproducibility. Based on the literature [Has08], we conclude user experience to be unique to an individual and influenced by several factors such as prior experiences and expectations related to those experiences. As user experience is related to users' perceptions, objective measures extensively used to evaluate the interactive systems therefore appears as insufficient for user centered design and evaluation. The collection of subjective and emotional data on the experience is a necessary step to understand the users. We address this challenge by using a mix of methods (e.g. field studies like contextual inquiry, lab studies such as listening sessions, and questionnaires) to gather requirements and later to evaluate our suggested designs. With the means of literature study on recent methods of systematic design process, we collected requirements for the sonification tool using contextual inquiry to better understand the context of use of sonification in climate science. These studies revealed how climate scientists work with their data, what kind of visualizations tools they use to analyse data, and how and where is an auditory display applicable in their workflow. The goal of focus groups was to find out if there is a metaphoric language that climate scientists use to communicate between themselves. We couldn't find any metaphors as the climate scientists communicated their tasks with a general data science language common in most scientific disciplines. The purpose of user studies on sound was to get an overview on their aesthetic preferences. The goal was not to run a thorough study on soundscape aesthetics and such a brief study would not give enough insight on that. There was a notion of skepticism towards auditory display in general which we decided to minimize by more contact with the climate scientists through collaborative stages of the project which we discuss in the following chapters.

5 SYSSON FRAMEWORK

Data exploration and interaction in visual interfaces has been vastly studied which has lead to visual design guidelines (Visual Information-Seeking Mantra [Sch96]), workspaces (Visage and Sage [RCK+97], and Snap-together Visualization [NoSh00]). Shneiderman [Sch96] described a Visual Information Seeking Mantra; "overview first, zoom and filter, then details-on-demand" that has been widely used as a principle in information visualization designs. Visage and Sage [RCK+97] presented a workspace that allows multiple visualization views. Some basic operations are supported across all the visualization views such as filter, copy, roll-up/drill down, and scale. Users can also manipulate the data in one visualization to extract what is relevant to the task and recognize the relevant data by dragging and dropping it to another view to automatically create a new visualization. North and Shneiderman emphasized the value of multiple coordinated visualizations in the Snap-Together visualization interface that empowers the users to mix and match visualizations and coordinations without programming.

Zhao [Zha06] investigated whether such techniques in visualizations can be transferred into auditory data exploration and adapted Shneiderman's approach to an auditory context. She created a framework to direct auditory interface designs for exploratory data analysis. The framework consists of a set of *Auditory Information Seeking Actions* (AISA) for accomplishing exploratory data analysis tasks that differ from visual actions, and a set of design components with general design issues for supporting AISAs. Many of the actions are similar to the Visual Information Seeking Mantra but include different cognitive processes and present special design challenges due to the highly transient nature of sounds. The four main components of AISA are:

- To provide a *gist*: gist is a short auditory message to convey the overall trend or pattern in data and may allow the detection of anomalies and outliers. Gist substitutes the word overview to avoid using a term that is related to "seeing".
- *Navigation* through the data space: browsing, searching, and exploring the data while listening to selected sections of it.Visual interfaces provide sustained display for users to directly manipulate. In auditory interfaces, users need to build a mental model of the display space and the navigation structures in order to efficiently move in the data set. In navigation, an auditory gist of the current data item or group of items can be a useful feedback from the system to the user.
- *Filtering* the data: Filtering undesired data in relation to some criteria helps to cut a large data set to a manageable size, and enables users to quickly focus on items of interest. In visualization, dynamic query paired with rapid display update (less than 100 milliseconds) is demanded [BE98]. In the auditory display, such a short time is usually not enough to demonstrate a gist of changes. It's better to present the results after filtering instead of continuous display updates during the filtering process.

- Providing *details on items on demand*: In a data space, users can select an item or a group of items to get details using auditory icons, earcons, or spearcons. It is hard to understand a data element without the suitable context. Furthermore, too much detail slows down the sequential presentation process and can be overwhelming for the users.

5.1. SYSSON FRAMEWORK: DESIGN COMPONENTS

In visual interfaces data is presented as visual attributes of objects in the virtual 2D environment and interaction with the data is often done
by using input devices to directly manipulate the visual objects on the computer screen. This is possible by the continuous, sustained feedback empowered by graphics display techniques and by a human's visual perceptual capabilities. This process cannot be directly transferred to the auditory mode, because sounds are perceived by human as transient/vanishing, time sensitive, and sequential.Therefore users must continuously create and maintain some navigation structures (mental representations) of the data space in order to interact with the data through the auditory interface.

Figure 5.1 illustrates the general design components in conjunction with data interactions in an auditory interface. Each AISA consists of one or multiple interaction loops in which the user uses an input device to issue a command and listen to the auditory feedback. The center of the loop is the data view that leads the navigation structure, allowing the user to build a mental representation of the data space and interpreting the auditory feedback.

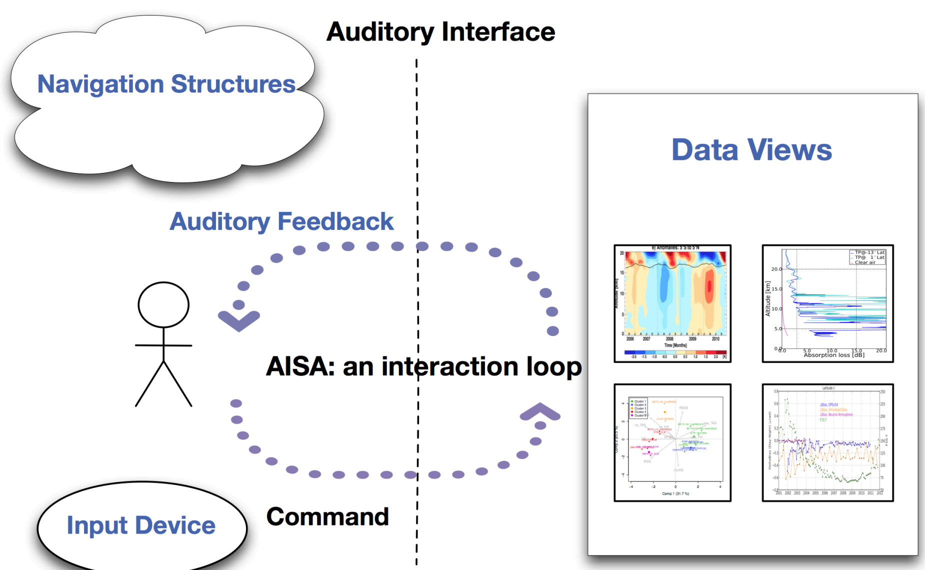

Fig. 5.1. Design components in AISA (adapted from [Zha06])

The main design purpose of SysSon was to allow development of new and modification of existing sonication designs iteratively. Using modular architecture allows decoupling components such as data handling, data processing, sound synthesis processes, mappings, playback approaches, and real-time interaction. All independent aspects of one sonification design can be re-used as starting points for new designs. The software resulting from the analysis of the preliminary Contextual Inquiry (Chapter 4) is a platform that links data processing, visualization, and auditory display. The framework has two front-ends for different

user's' purposes and skills; first as an analytical tool for the climate scientists and second as a development environment for expert users (sonification experts and sound designers). The second group has the option of editing and compiling new sonification scripts in an interactive shell (explained in Section 5.1.3. Figure 5.6). This option is also open for the first group in case the domain scientists are interested in exploring the sound domain further and taking over the role of co-designers.

5.1.1. DATA VIEW, DATA SOURCE, and DATA STRUCTURE

In visual displays, an external representation that relates to the task can help the memory of the user [Zhang94]. Choosing the proper data view for a given task would substantially affect performance in auditory interfaces[ZPSD04] [BE98]. For example, Flowers et al. [FBT97] suggested a sonified bivariate scatterplot to display the correlation relation of bivariate data, rather than a line graph sonified as two pitch-coded sound streams (one for each variable) in different spatial channels. SysSon provides two highly coordinated data views – a region(latitude, longitude, pressure level)-by-variable table, and a map. Figure 5.2. shows an example of table data view in SysSon platform.

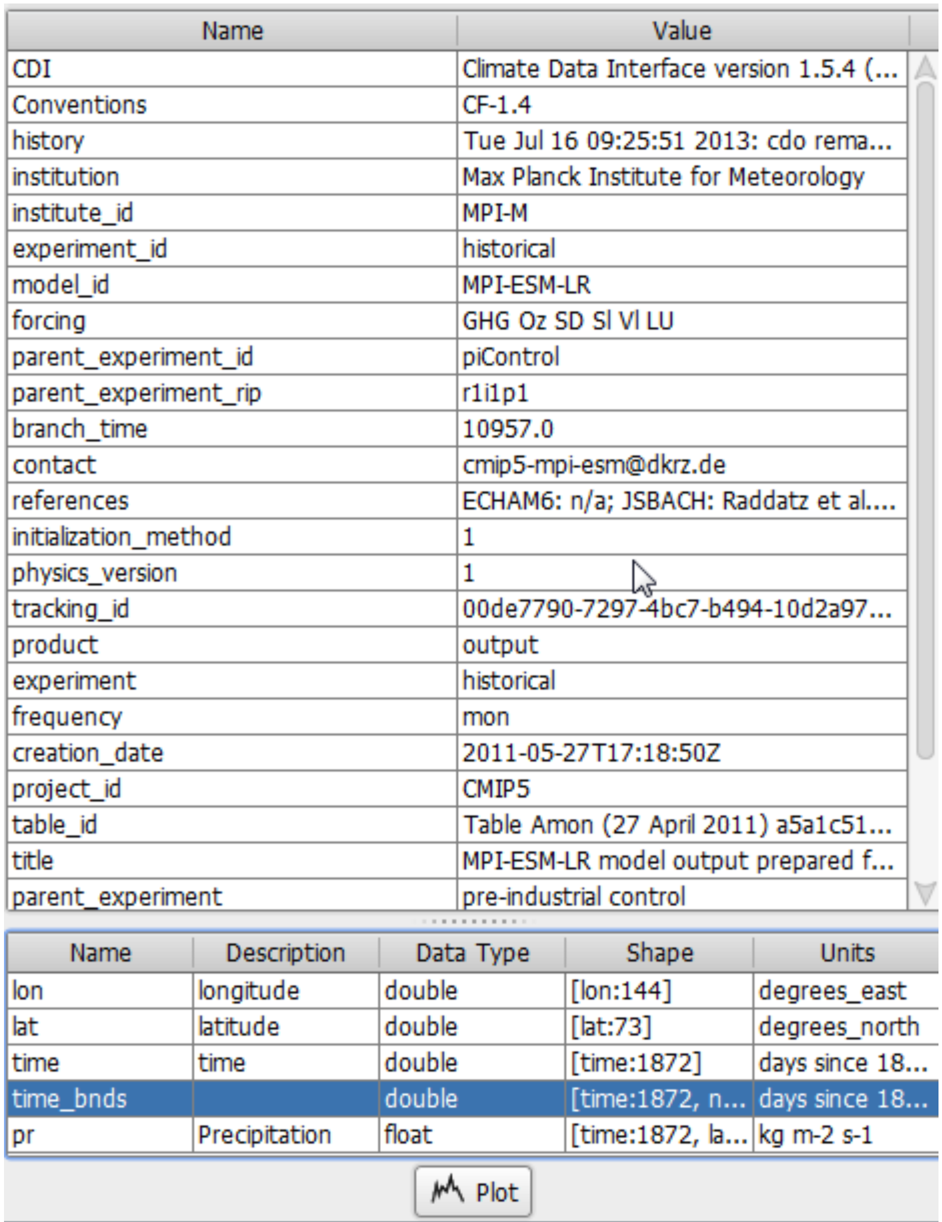

Figure 5.2. A Data Source View from Precipitation Data Using SysSon Platform

Climate data sets for sonification are usually very large, and domain scientists at Wegener Center use NetCDF file formats to store them. SysSon supports NetCDF (Network Common Data Form) [ReDa90], a format used in creation, access, and sharing of array-oriented scientific data. NetCDF files can easily grow to hundreds of megabytes, and in SysSon they are therefore not copied but simply connected to workspaces[13] as external references through handles called data-sources. Figure 5.3. shows an example workspace containing data-sources, sonification models, an audio-file, and plots. When a data-source is created, its data structure consisting of a number of variable

[13] The workspace contains all the data sources and the parameterized sonification instances. For more details on workspaces, check out the project wiki: https://github.com/iem-projects/sysson/wiki/Introduction

descriptors or attributes is stored in a matrix with the workspace, allowing to operate even when the related NetCDF file is offline. A matrix is a one or multidimensional structure of floating point cells. Dimensions are represented by other matrices. For example, a matrix of temperature 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. Matrices 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. Transformations such as dimension reduction, or sub-sampling are possible in SysSon framework.

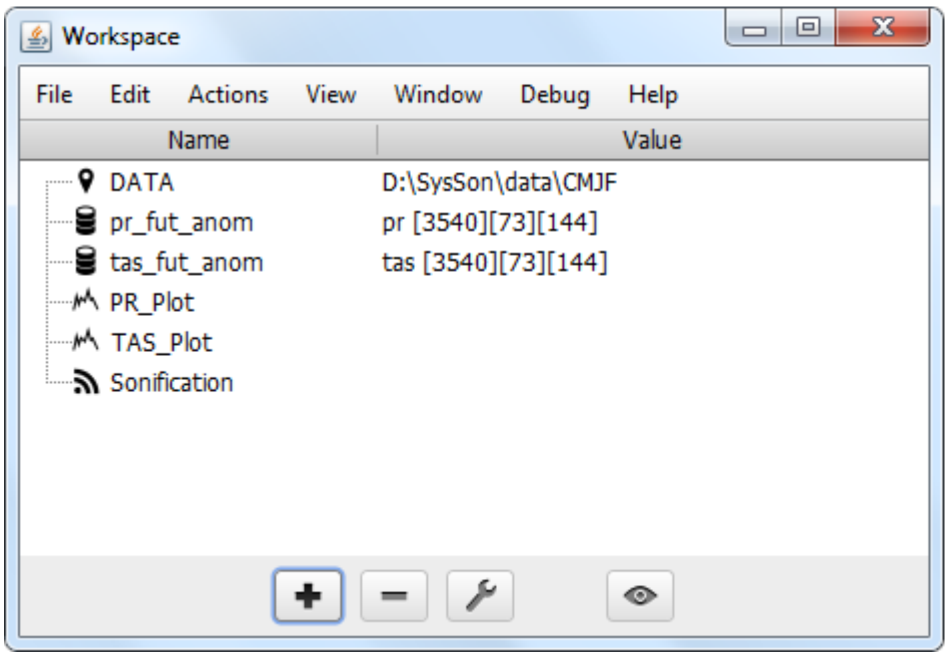

Figure 5.3. Workspace of SysSon platform

For example, to produce a time slice of a temperature matrix, the dimension-selector would indicate the time dimension and the reduction-operator is an index into the time dimension. Sub-sampling is possible 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.

5.1.2. NAVIGATION STRUCTURE

The workspace for SysSon platform is a root folder that provides a graphical user interface for sound processes. The creation and modification of objects inside the workspace are automatically synchronised with an underlying database. Therefore, the user can preserve and come back to the workspace at any later point and will find everything in its previous state, including for example the sonification models or plot objects. The GUI uses metaphors of a standard desktop application such as point-and-click, drag-and-drop, and undo-redo.

5.1.3. PLOTTING AND SONIFICATION GUI

The graphical user interface (GUI) allows users to parameterise and explore predefined sonification designs with their own data sets. The main component of the interactive GUI consists of a plotting interface and a sonification interface. Users can interact with this interface by uploading a data set, zooming in and out of a plot, and exploring different dimensions of the data by using sliders. Plot objects include a matrix, a mapping from dimensions to axes, and visual parameters such as colour palette and scaling. Fig. 5.4 shows an example plot of a time slice of precipitation data.

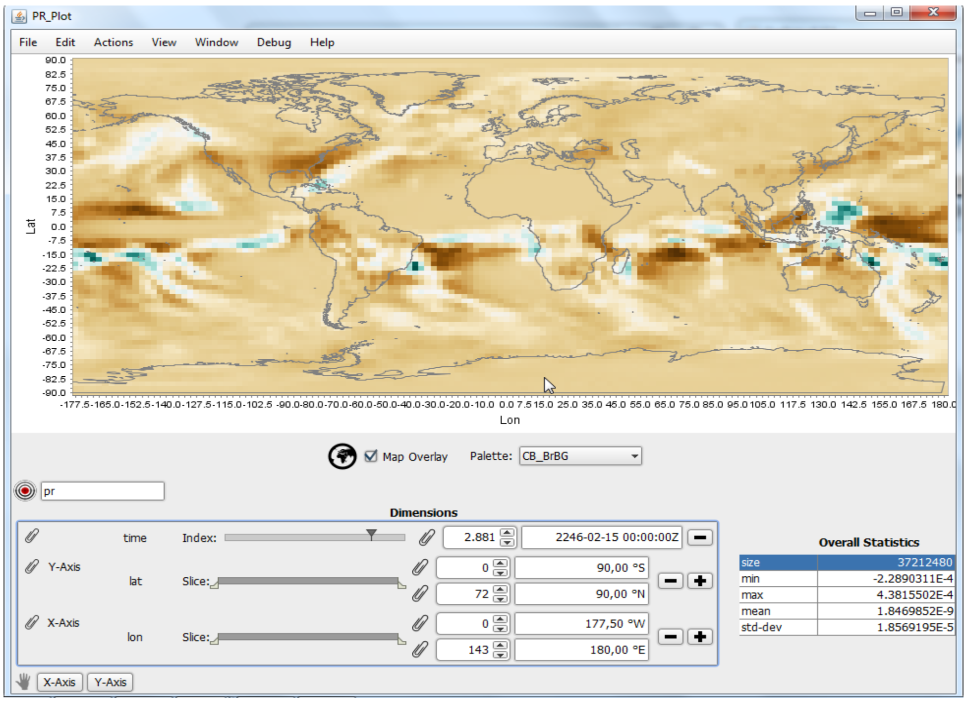

Fig. 5.4. Plot View

The sonification user interface is shown in Fig. 5.5 The *Mapping* area of the GUI shows that the model uses a data source which is linked to a matrix *pr* and a matrix tas(pr stands for precipitation and tas is for surface temperature.) This matrix has been reduced to small sections of *latitudes* and *longitudes*. The matrix's dimensions *time* and *lon* are mapped to the sound dimensions *time* and *panning*.

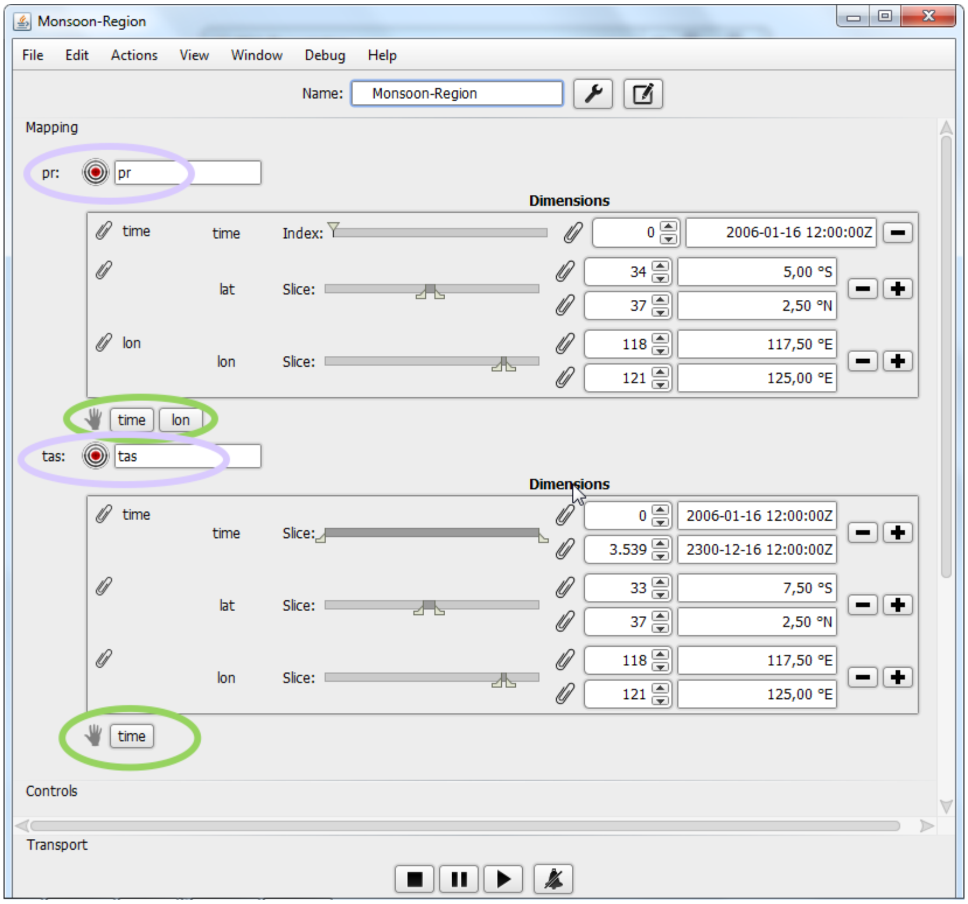

Fig. 5.5. Sonification View

The sonification designer can open an integrated code editor within the workspace to develop the sound models. This is illustrated in Figure. 5.6. The programming language used for the editor is ScalaCollider.[14] The 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. 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 for the novice user, steeper. The choice of ScalaCollider was outside of the author's purview. Some reasons for choosing ScalaCollider include: combining object-orientation and

[14] ScalaCollider is a sound-synthesis programming language, a dialect of SuperCollider based on the Scala language.

functional programming, running on Java Virtual Machine (it can be combined with other Java libraries and is operating system independent.), type-safety, performance, and doing away with the split-up of SC-Lang (compiled classes, interpreted code, C primitives, GUI server), by allowing all those inside the same language.

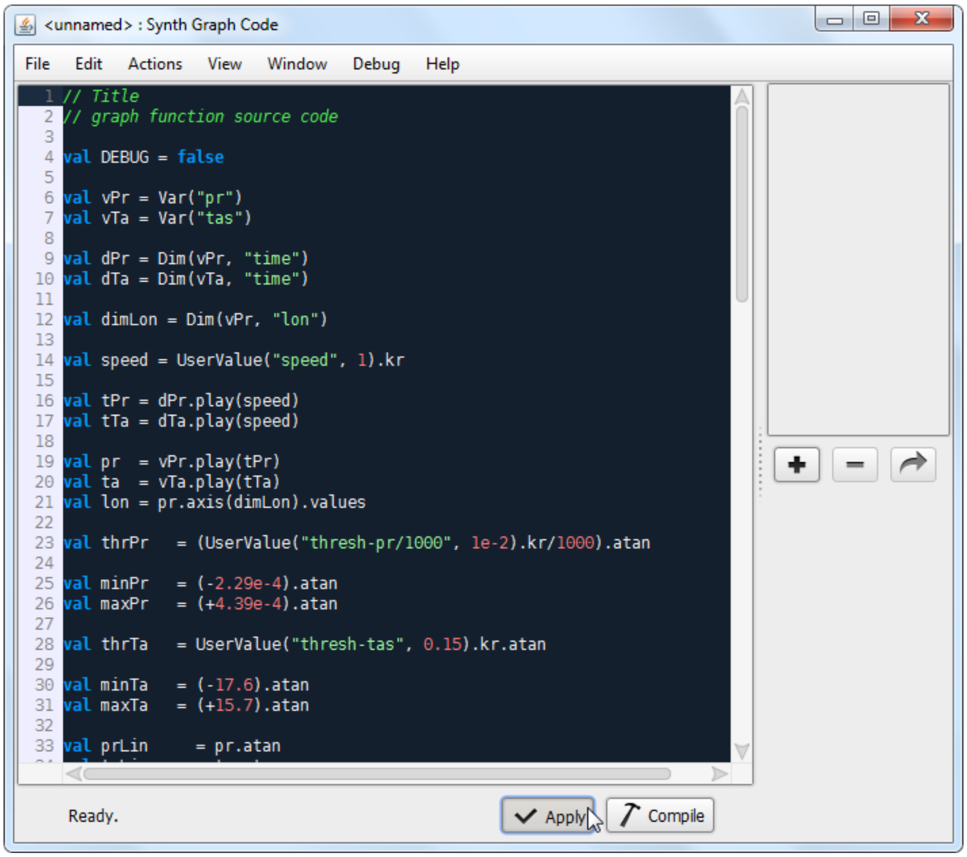

Fig. 5.6. Sonification Code Editor

5.2. USABILITY TESTS

As discussed in chapter 3.6, usability tests are necessary throughout the design life cycle to identifying users' needs and establishing specificity of requirements. While SysSon software was at alpha stage[15], we took it to the climate scientists for a set of usability tests. Eleven climate scientists (4 female/7 male - from three different research groups) volunteered to participate in our qualitative interviews (verbal protocols). Two of them were excluded from analysis (because one did not talk loud enough, a second one was associated to a research group that was too different from the rest) leaving 9 interviews for further analysis. For most cases (except for one), two interviewers were present, with one as interviewer and the other as observer (and occasionally also asking questions). Participants were asked and encouraged to think aloud and describe what they

[15] The alpha phase of the release life cycle is the first phase to begin software testing.

were doing. Semi-structured interviews were conducted parallel to participants exploring the tool, including questions regarding user interface as well as clarity of sonified climate data. The interviews consisted in part of a walk-through description of the tool by project members for the climate scientists, which usually 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.

Bonebright and Flowers [BoFl11] suggest that experimental procedures should be developed according to the particular goals of a sonification application. The usability study was designed so as to emulate the natural workflow of the climate scientists. 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. 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 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 (chapter 4.3.1), namely a comparison task. However, comparing different climate models or different data sets is time-consuming and within 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 GUI.

Two tasks were planned:

- In the first task, 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 (also possibly changing the location). They listened to parallel sonifications, either varying the time axis or the geographical dimensions (latitude/longitude). They were asked to open two workspaces simultaneously and then to design two sonifications to later listen to.

Due to limitations of the then current software implementation, strictly parallel listening was impossible. (users had to open two workspaces and press start and top manually which caused a few seconds delay in case of listening simultaneously) 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 documentation was 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 to accommodate to the interview's context. Additionally, unsystematic observation protocols were drafted of most sessions, capturing aspects of the interview situation to facilitate analysis. Two pilot tests were held at Wegener Center to ensure that the instructions were clear enough. These were not included in the analysis.

5.2.1. PROCEDURE OF DATA ANALYSIS

Analysis of data from usability tests at Wegener Center was twofold: data collected concerning the interaction with the software. This material included usability issues that informed the further development of the software. Second, the qualitative material on the attitudes of the scientists in comparison with data collected during the first round of interviews by contextual inquiry (Chapter4). The latter is also analysed by Reichman [Stefan Reichman's thesis] in sociological context.

Data analysis proceeded via an open coding strategy [StCo90] towards heuristic categorization. However, the requirements of developing a grounded theory were only partially met. Böhm [Boe10] suggests that the Grounded Theory approach encompasses the entire research process. Hence, only data analysis was carried out according to Strauss and Corbin's recommendations [StCo90]. The principal method consisted of a constant comparison of codes and empirical data to work out similarities/dissimilarities in the phenomena: Once a theory starts to emerge from the data, the idea is to confront theory with the data in an iterative process until no new information can be obtained (theoretical saturation).

The result is a system of codes, (heuristic) concepts that can be either named according to what was actually said by the participants, or later by the researcher[Boe10]. A category is an abstract code that (ideally, but not necessarily) combines codes of various phenomena. The aim is to surpass mere (paraphrasing) description. The result of an open coding process is an analytical description of the phenomena that refrains from using theoretical concepts but instead relies on the concepts/conceptualizations used by the test subjects themselves. The overall intention was to reconstruct recurrent opinions regarding the possible uses of sonification within our target community. The data we collected seem to be too heterogeneous (probably due to the small number of participants and all from the same research center) to allow for systematic categorization (unless one takes into account the possibility of categories with only one instantiation).

5.2.2. RESULTS OF USABILITY STUDIES

The results of the usability studies can be grouped into two categories: data concerning usability issues (comments on the functionality of the sonification platform), and attitudes towards sonification in general. Analyzing notes and observations from usability studies, three categories of usability issues were gathered: plotting, sonification, and navigation. Each category comprises several issues to be tackled by improving the software in the next iterations (see Table 5.1. for details). Some functions in the plotting window were missing such as zooming, scaling, changeable color scheme, and indexes for latitude and longitude. Furthermore, the color scheme used was considered ambiguous. Climate scientists deemed a more standard color scheme desirable. Concerning the sonification window, the climate scientists expressed their desire to have options and controls such as mute and pause buttons. Moreover, they expressed interest in the options for simultaneous playback of two data sets as well as different slicing options. 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 (shown in Fig 5.4, section 5.1.3). 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.

Usability Issue	Sub-Category
Plotting Window	- Zooming and Scaling - Color scheme - Indexing Latitude/Longitude
Sonification Window	- Mute/ Pause options - Parallel playback option - Different slicing options
Navigation	- “plus”-button unclear - undo options not available - file paths/ directories unclear

Table. 5.1. Usability Issues found during the user studies

The questionnaires used in Contextual Inquiry (Chapter 4) 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. Understanding their visualization tools and their workflow was another central point. In the Usability Tests, the questions were more task specific and focused on usability and learnability aspects of the SysSon tool. The cultural bias against 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 a sinus tone oscillator which was received as 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 limited duration of the experiments. Working with the same sounds for longer time periods would in all probability yield different results.

One of the main questions in both studies was whether the climate scientists would use the sonification tool for data analysis. The answers varied between the Contextual Inquiry and the Usability Testing, which we believe is an effect of the possibility to explore actual sonifications during the Usability Testing. The direct answer to this question during the Contextual Inquiry was mostly yes with a few maybes, but when the climate scientists were asked to explain their answers, they were more skeptical and said they would like to see how such a tool works first in order to be able to say whether they would use it or not. During the usability studies, only two of the participants were very skeptical and only one of them refused to use the tool for data exploration/analysis.

There is a considerable portion of skepticism towards sonification of data in general in the group we studied. This skepticism concerns issues of temporality as well as learnability and applicability[16]: *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.*

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:

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[16] As memory issues are discussed in Chapter 2, these are main concerns in any auditory display. The purpose is not to skip these issues, but to find optimal data analysis tasks that focus on strengths of our ears.

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.*

5.2.3 USABILITY STUDIES WITH SOUND EXPERTS

A second round of usability tests were conducted at IEM a few months later with a later version of the software. The aim of this round was to get a general feedback on usability issues from a computer-musician/ sound-expert standpoint. Six members of IEM volunteered and were divided into three groups of two plus a project member in each team. The sessions included a twenty minute introduction to the tool, and semi-structured qualitative interviews in an interactive format(up to an hour). Tasks such as exploring parameter ranges, comparing the data sets from different regions by listening to them, tweaking the sonification on the GUI, and by modulating the source code on the code editor, were planned. Tasks were all related to sonification of anomalies[17] of near surface temperature and precipitation. Four different regions were selected for the participants to listen to: A region with high temperature anomalies and high precipitation anomalies, one with high temperature anomalies and low precipitation anomalies, another one with low temperature anomalies and high precipitation anomalies, and finally one with low temperature anomalies and low precipitation anomalies. Granular synthesis [Roa88] was used for sonification of data. Grain pitch was mapped to temperature, density and shape of envelope depended on precipitation. This round of usability study was not audio recorded. Participants filled out questionnaires after the usability study, and the project members drafted observation protocols on how their group worked. (Questionnaires could be found in Appendix C). In Spite of improvements of the software tool comparing to the previous usability studies, there were still several usability issues that the participants commented on. Some similarities we found in all three groups regarding their interaction with SysSon framework were:

- All participants only spend time on the GUI and not on text based code editor at all. (they all mentioned that there was too little time to learn)

[17] Anomaly means a departure from a reference value or long-term average. For example in our selected data sets temperature anomalies are deviation from the mean value over the same month in 30 years (e.g., January 2030 = January 2030 – Mean(Januaries 2015-2029; Januaries 2031-2045)

- Anomalies were not a good choice for the first time to get familiar with sonification of climate data. It took a long time till they understood the concept and in such a time crunch we should have used more time for sonification
- All three groups only tweaked the sound slightly, non of them created a new sound or sonification model
- They said they would use the tool for data analysis and not for sound creation (probably because we haven't shown the whole potential of the tool in such a short time)

The only difference between groups was that each group spent a different amount of time on plotting components.

5.3. DISCUSSION

Not all issues related to usability could be resolved within the span of the project. The critical issues were prioritized and only the most crucial ones could be rectified. Overall building the SysSon platform on top of a large host environment (Sound Processes) was both advantageous and disadvantageous for the project. While large issues such as data handling and sound synthesis were easier to resolve within a larger framework, specific climate sonification scenarios within usability tests required a lot more time and training. Many usability issues arose from the complex nature of the underlying structure that eventually needed to be resolved in the next iterations of the software.

The analysis of usability 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 large and multivariate data; they acknowledge sonification as being especially appropriate 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 INTERDISCIPLINARY WORKSHOP

Scientists try to identify the components of existing structures; designers try to shape the components of new structures.

Christopher Alexander - Notes on the Synthesis of Form

In sonification of scientific data, designers know very little about the domain science and domain scientists are not familiar with the sonification methodology. The knowledge about the domain science is not given, but evolved during the problem-solving process. As discussed in previous chapters, some design challenges in auditory display regarding user-centered approaches are explored and involvement of domain scientists throughout sonification designs is suggested. We explored this within a workshop in which sonification experts, domain experts, and programmers worked together to better understand and solve problems collaboratively. The sonification framework that is used during the workshops is described in the previous chapter and the workshop process and how each group worked together during the workshop sessions are examined. Participants worked on pre-defined and exploratory tasks to sonify climate data. Furthermore, they grasped each other's domains; climate scientists especially became more open to use auditory display and sonification as a tool in their data analysis tasks. Resulting sonification prototypes and workshop sessions are documented on a wiki to be used by the sonification community. To get started, we used some of the sonification designs created during the workshop for an online study where participants from science, engineering, and humanities were asked questions about the data behavior by listening to sonifcations of bivariate time series which is reported at the end of this chapter.

Frauenberger and Stockman showed that the design process for auditory display is mostly unstructured and it provides limited support to reuse the design knowledge created [FrSt09]. 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 [deC07]. Other tools, such as Sonification Sandbox [WaCo03] 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. We tried to include the users actively in every stage of the design process. Some of their active roles were: choosing and making data sets available that are more challenging for them to analyse[18], early stage usability tests of the tool[19], suggesting the missing features, thinking and solving sonification problems with us throughout the interdisciplinary workshop.

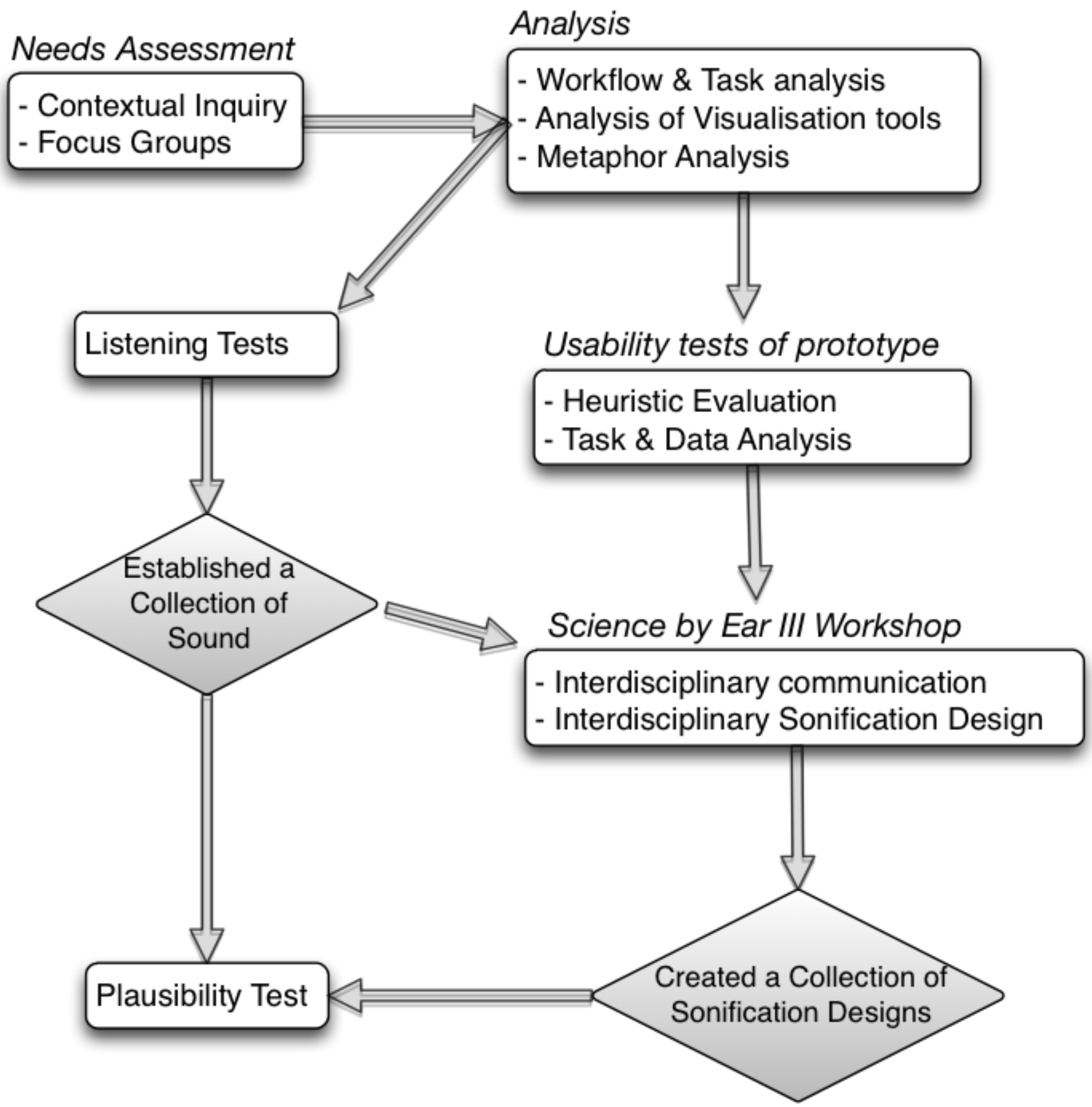

Figure 6.1. An Overview of the Design Process

Sonification of scientific data requires understanding and expertise in the domain science, sonification design, and software engineering. In order to create useful sonifications, experts

[18] Explained in chapter 4.
[19] Details in chapter 5.

design and develop sonification systems iteratively working with the domain scientists. In SysSon project the aim was to create an interdisciplinary sonification platform which enables climate scientists and sonification researchers to generate sonifications systematically. Climate scientists from Wegener Center provided a huge variety of measured and simulated climate data for this project. The starting point for our approach were previous interdisciplinary sonification workshops which had a broader user group than our project. In **Science by Ear I and II** [dDFV+06] workshops domain scientists from different scientific domains with a variety of data (e.g. medical data, sociological data, physics data) participated. Our focal point was one specific domain with a variety and complexity of data sets and problems within this domain. Figure 6.1 provides an overview of various stages of the design process used in our interdisciplinary approach.

6.1. PARTICIPATORY DESIGN APPROACH

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 advanced during the design. In such a continual process, users become co-designers not only at design time, but also throughout the whole existence of the sonification system. Rather than presenting users with closed systems or predefined sonifications, we intended 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 [NoDr86] and participatory design, but we tried to extend our approach in parts to meta-design [GiFi08] to shift some control from designers to the domain scientists (this approach didn't fully succeed due to complexity and lack of time) by empowering them to create and contribute their own objectives in the sonification design method. The participation of the users in the design decisions go beyond the processes at the design time.[20] We particularly included participatory design [ScNa93] to involve users in the co-design process with the sonification designers. Participatory design (PD) is a process that uses early and continual inclusion of the users to produce a technology, such that they actively involve in setting design decisions and planning prototype [CCRN00].

The basic rationale behind PD is users' participation in design by involving them in decisions that affect them and the practical issue of accessing their extensive domain knowledge. Moreover, users need to have a sense of ownership in order to make better use of the technology. This concept is first introduced by Scandinavian researchers who tried to rely on union-sponsored workshops and games involving direct interaction between designers and workers [Gre03]. They showed that workers who can employ certain control over their work tend to be more motivated and develop

[20] See chapter 3.4. for details on design time.

more efficient and effective work practices. Technologies are worthless on their own; it is users' expertise that makes them valuable. Some users may simply use a limited set of functionality and ignore the potential value of the technology while others can use it creatively [Yam10]. User participation is an effective technique to empower users.

PD is still developing and hence its research design tends to be adaptable. The later work in PD has tended to add targeted interaction with less intrusive methods such as observation and artifact analysis. According to Spinuzzi [Spi05] three basic stages in most PD research are:

1. Initial exploration of work; designers meet the users and familiarize themselves with the ways in which the users work together. This exploration includes the technologies used, but also includes workflow and work procedures, routines, teamwork, and other aspects of the work. (similar to contextual inquiry we did in chapter 4)

2. Discovery processes; designers and users employ various techniques to understand and prioritize work organization to clarify the users' goals and values and to agree on the desired outcome of the project. This stage is often conducted on site.

3. Prototyping; designers and users iteratively shape technological artifacts to fit into the workplace envisioned in Stage 2. Prototyping can be conducted on site or in a lab; involves one or more users; and can be conducted on-the-job if the prototype is a working prototype.

Some techniques of contemporary PD include but are not limited to: ***video brainstorming*** [Mackay], structured brainstorming or ***Bootleging*** [Hol08], and the more physical technique: ***Bodystorming*** [OKK03]. Bootlegging is a structured brainstorming method that is suitable to generate several ideas within a very multidisciplinary workshop. It's not suited for our workshop because our tasks were not as random and the project was not in such an early stage to benefit from a vast number of ideas. We rather needed a more focused technique.

Participatory workshops adopt the principles of PD by shrinking the user involvement into workshop sessions. The workshops are brisk and powerful tools that help designers to find out specific activities and situations without a thorough investigation of the context. Common PD techniques such as paper prototyping and storyboarding are more suitable for GUI design rather than auditory display design. The adaptation of some of these techniques in the design of an auditory interface in the context of a multidisciplinary workshop has been previously investigated e.g. in [DrWa06], [Sva04], and [Tax04]. More specifically in the context of data sonification deCampo et al. investigated participatory workshops within the scientific context. Participatory workshop settings have been useful in utilizing participants' creativity [NTTA+08] by simulating environments using role playing [DrWa06], [Sva04], or in establishing a hands on experience for the users in an iterative process [Tax04]. The last approach is the closest to our use of participatory workshop. Given the systemic and experiential nature of our sonification environment, we decided that a participatory workshop as an alternative to controlled experiments could be more useful in the early stages of sonification design. Although we used a sequential process throughout the project, this workshop was a standalone component of the design to involve other stakeholders and sonification experts from other institutions. The users worked with a bigger group of sonification experts than they were usually working with during the project. This lead to an almost equal number of sound experts and climate scientists in the process of co-design which created a designer-designer interactive atmosphere rather than designer-user atmosphere. Additionally, we suggest a long-term inclusion of users or user representatives within the design team to be continued after the workshop. Despite the advantages of PD 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 [deC07] 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 relevant design space. Our 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. Figure 6.2 shows the intended scheme of collaborative and individual spheres for climate scientists and sound experts within the platform. As described in previous chapter, both groups could work on the same tasks and context. The same script and it's configurations could be edited by sonification designers through coding or by climate scientists using the graphical user interface. This form of collaboration is designed and developed in within the platform and makes it possible for both sonification designers and climate scientists to contribute. However, during the workshop the climate scientists were not equipped with their own computers and therefore did not contribute directly into the final sonification designs, but indirectly they were the decision makers regarding several aspects.

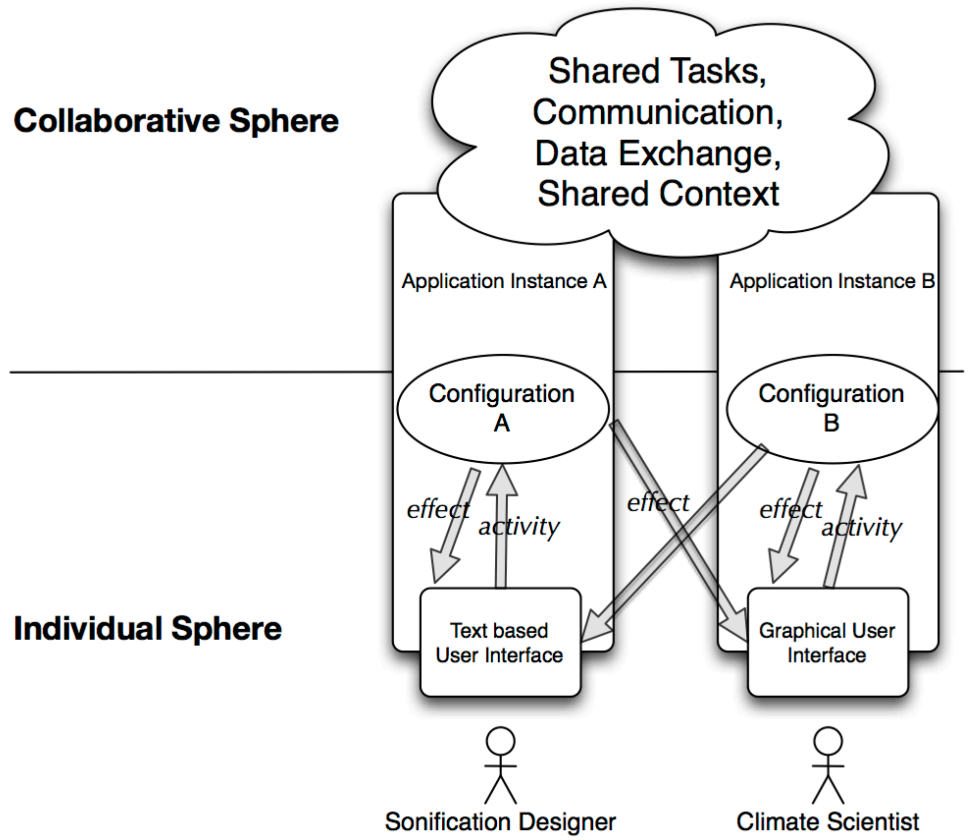

Figure 6.2. Collaboration between Domain Scientists (Climate Scientists) and Sound Experts in an optimal Shared Context Scenario.

6.2. WORKSHOP SETUP AND PROCEDURE

As described at the beginning of this chapter, user centered and participatory design are used to collaboratively create sonification solutions to the climate scientists' problems. This collaborative research process was compacted into an experimental Science By Ear III 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[21] within groups and discussions between all groups at the end of each hack session. Hack sessions lasted between 2 to 4 hours and 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.

As Hoffman et al. [HSBK94] suggest to eliciting knowledge from experts through brainstorming; the idea generation in the workshop was based on brainstorming sessions, in which participants were asked to generate creative decisions within the first half of the sessions. Climate scientists discussed and identified potentially more interesting research questions within the data sets used in the task. In the meanwhile, sonification experts made suggestions on mapping and sound design. These ideas were collected by session facilitators (project team) in the wiki pages of the workshop. This process helped both groups to understand problem-solving methods of one another. In the second section of each session, ideas were selected from collections of the first half through interdisciplinary discussions. Usually one or two ideas that were more feasible for the programmers were chosen. The dynamic and experimental nature of the collaboration made it more difficult to stick to the pre-defined tasks and finally each group focused on one of these two; the data and research questions that were more interesting for the climate scientists in that specific team, or the ones that were more manageable to sonify within a short amount of time for the audio programmers. Finally, each group or subgroup worked extensively on implementation of the ideas within the sonification tool. This process helped sonification experts to understand what makes sense for climate scientists to listen to, and helped the climate scientists to get a hands-on experience on sonification of data and the sound creation process.

6.2.1 FIRST SESSION: BIVARIATE DATA

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

[21] According to hackathon.guide, hacking is creative problem solving. A hackathon or hack session is any event of any duration where people come together to solve problems. Participants typically form groups of about 2-5 individuals, take out their laptops (if the event is technology themed), and dive into problems.

metaphoric sonification designs to distinguish between temperature and precipitation changes, and compare the zonal data sets to the full range of data sets.

The resulting sonification strategies: the sonification approach in the first group 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 stereo panning for east - west mapping.
- Using noise gate to display only data above a certain threshold.

The climate scientists suggested combining 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.

The second 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. Furthermore, 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: OPEN TASK

As mentioned before, for this session we did not use the predefined 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 not very strict and the participants were able to switch between different groups during different sessions.

The first 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.

The second 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 were 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.

6.2.3 THIRD SESSION: EXPLORING DIFFERENT TASKS

The first 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. This session did not have any useful sonification patches as results. 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. Furthermore, workshop participants had challenges regarding ScalaCollider language that are mentioned in Chapter 5.1.3.

The second 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.

6.3. 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 was 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.

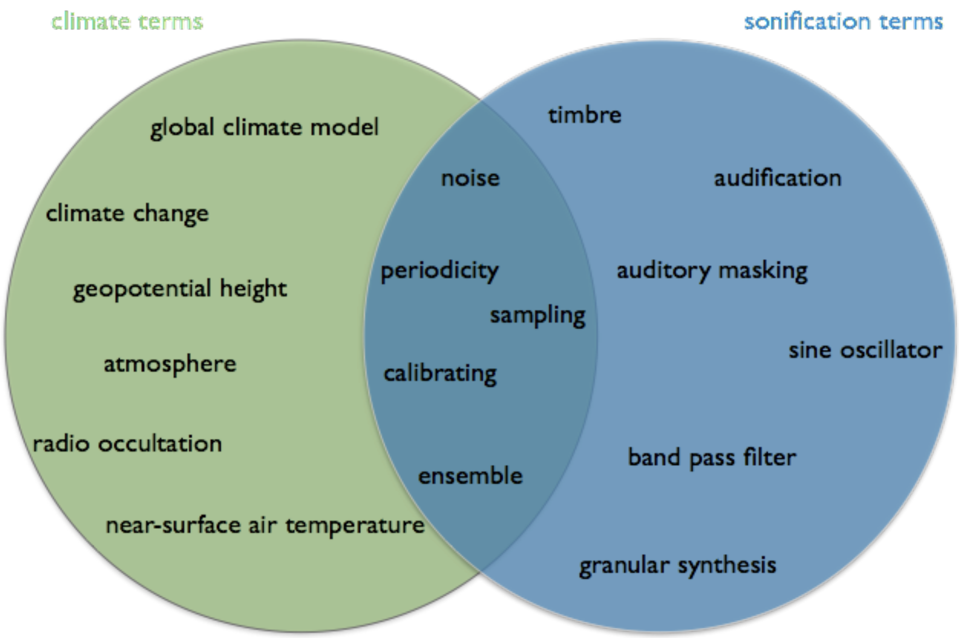

Fig. 6.3. Domain Specific Terms used in Pre-Workshop Questionnaire.

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 Figure 6.3. Additionally, terms chosen for this task were either used during the introductory plenary at the beginning of the workshop, or were discussed during the hack sessions or discussions due to the use of them in the tasks. The goal of such brief questionnaire was to see if experts get familiar with each other’s vocabulary within such a short time. All participants had 30 mins time to describe 11 words in both pre and post questionnaire. If the answers were close to the description of the words in textbooks, they were considered as correct. Results from pre and post questionnaires showed that the understanding of the terms and vocabulary in 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.

6.4. REFLECTIONS ON THE WORKSHOP PROCESS

Based on feedback from the participants, the collaborative nature of the workshop was very refreshing and innovative but there were several bumps regarding the execution and implementation. 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.

One of the main issues 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[22] was very challenging and time consuming in some sessions. The steep learning curve of ScalaCollider and the sparsity of its documentation didn't make this challenge any easier. Additionally, having a workshop at the early stages of the software development cycle worked as a usability test with expert users instead of a fully functional workshop. 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.

6.5. A STUDY WITH THE RESULTING SONIFICATIONS

The purpose of this brief study was to use a sonification designed by the interdisciplinary groups at the workshop and evaluate it by random scientists, engineers, and sound experts who were not involved in the design process. The study was supposed to explore all or parts of the following questions:

- Can participants use one of the sonification algorithms designed at the workshop to detect similarity of two time series?
- Can participants hear cyclic patterns and their consistency in the data?
- Can they hear multiple streams of data using our auditory representation?
- How do they interpret these sonic representations of data with their own words?

[22] The programmers participated in the workshop were expert in Audio programming languages related to ScalaCollider (such as SuperCollider). However, they were not directly ScalaCollider users.

Data sets: We decided to use the data sets that were used most at the Science by Ear III workshop and the sonification design which both groups at the workshop spent the longest time on creating. The sonification of near surface temperature and precipitation data that was created during the first task by both groups and refined during the second task by one group, was chosen. Data sets were from two very different regions (one from Monsoon area where temperature and precipitation are highly interacting, and one from Colorado where precipitation is present in all seasons and the temperatures are significantly lower than the other region, were selected.)

Procedure: The study was performed online and the website contained a questionnaire to be filled by the participants and sound samples to listen to. The structure of the questionnaire was as following:

- Demographic information: field of education or work, years of experience in the field.
- Familiarity with sound or music
- Familiarity with data science
- An introduction to sonification in general
- A listening section: participants were supposed to listen to the sound samples as many times as they wish.
- Evaluation sections: participants received two sets of questions. The first section included sound samples and questions regarding those sound samples. The second section included comparison tasks regarding two sets of sound samples. The structure of the evaluation section was as following:

First Section: Listen to the sound sample, representing some data and answer the following questions:

1. Do you hear a trend in data? If yes, describe it.
2. How many different types of sound do you hear?
3. Is the sound ascending? descending? or stable?
4. Do you hear periodicity in sound? If yes, how many repetitions?
5. Could you hear the number of occurrences of the noisy sound? If yes, how many times?

This section was designed to check the user's ability to detect changes in data and to test the general ability of the user to understand auditory information.

Second Section: Listen to the following three sound sequences and say which of the three is more different from the other two? and describe the difference with your own words. This task was designed to test the user's ability to perform similarity search in the designed sonifications.

Research hypothesis: We tested some basic tasks to explore if our sonification designs could help in hearing climate data patterns. We explored the hearing of the participants regarding their age, occupation, musical/sound experience, and their data analysis experience. By the participant's performance, we mean the total number of correct answers the participant gave to the questions of the listening section. The study included very simple time series. Each correct answer to a multiple-choice question has received one point. No points were deducted for a wrong answer. The right answer is if the participants hear the trend (ascending/descending) in data, the number of data streams, or the number of cycles in audio signals.

Participants: The study was carried out using an online user study. The web address was posted on audio, science, and engineering mailing lists. All the information was posted on the website and no previous experience in data mining, climate science, or sonification was required. 28 subjects took part in the study. 60% of participants deal with data mining and data analysis tasks in their job (mainly using matlab, R, and MS Excel), and 70% of them have sound or music experience.

Results: According to the results of ANOVA test, there was no statistically significant difference in total scores across different sound experience, data analysis experience, or occupation groups in general. However, we have found a statistically significant difference in total scores between two specific occupation groups. Figure 6.4 (left) shows the average performance of two occupation groups; {natural sciences, engineering} versus {humanities, art}. There was no significant effect of familiarity with data analysis on the performance at the $p < .05$ level for the conditions $F(1,26) = 2.2916$, $p = 4.2252$.

Although subjects without any musical or sound experience certainly performed worse (ave = 62.5% of cases) than sound experts; their average performance was similar (ave = 61,90 % of cases) to the participants with little musical experience. (1-5 years). Thus, the amount of musical experience seems to matter for the experienced subjects' performance for these short hearing tasks. Figure 6.4 (right) shows the level of performances with different level of experience in music and sound.

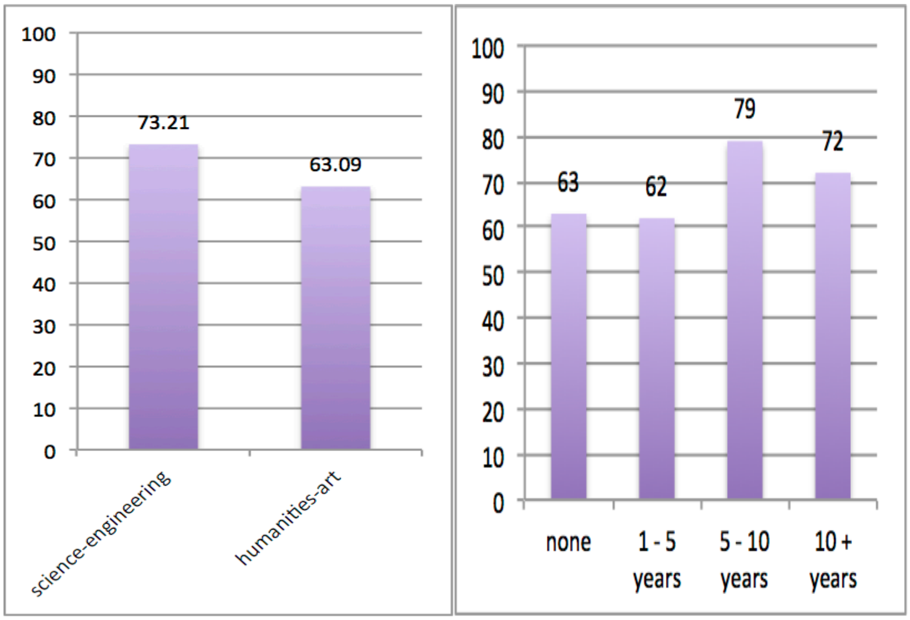

Fig. 6.4. The effect of occupation (left) and the effect of musical experience (right) on performance.

Qualitative results: Analysis of descriptions of the sounds by participants shows that all who could hear repetitions in sounds could also explain them as oscillations or periodic impulses. The majority of participants could also explain the noisy parts of sounds and distinguish them from the other sound textures. A few have also described noisy sounds as more scratching, or with higher density content. The average number of correct answers related to sound was 72.26 percent of the cases, which is relatively high for participants who are not familiar with sonification at all.

6.6. DISCUSSION

We investigated the participatory design process for an auditory display and proposed a multifaceted framework. The purpose of using such a framework in a participatory context was to provide the possibility to create shared design knowledge in sonification and building new sonification designs on top of the prior work. From the early stages of the project involving the domain scientists in the process seemed to be an obvious choice. The process worked only in the sense that we gathered a diverse set of data analysis problems, solutions, and methods that work for data scientists within our sonification framework.

One of the main challenges that we had throughout the process is the domain scientist's skepticism towards sonification and auditory display as a useful tool. The multidisciplinary workshop helped to reduce this skepticism due to the hands-on nature of the hack sessions. The participation of the domain scientists in form of brainstorming sessions was essential but not sufficient. The critical point is that the scientists would not keep on using a framework unless they get hands on experience programming with their own computer at their own workplace. The complexity and steep learning curve of the sonification tool made such an involvement unmanageable. Regular use of the software can improve the involvement of the domain scientists. Due to the gap between different stages of the project and coordination between different institutions, regular (e.g. monthly) hack sessions at the final stages of the project did not take place.

Finally, the concept of collaborative and participatory design approach fully depends on the support of the community around it. We need to integrate the domain scientists and other sonification experts to use and contribute to the open source software environment in order to transfer and exchange sonification design knowledge. The hope is that this approach and approaches similar to this enable sonification designers and domain scientists to build on each other's works and encourage them to contribute long term in creation of sonification designs efficiently.

7 CONCLUSIONS

The work presented in this thesis looked into the design process of sonifications from human-computer interaction perspective and proposed a framework of methods to aid the transfer of design knowledge throughout the problem solving lifecycle. The introduction motivated the work and set out the research questions and aims, defining the scope and the potential contributions. The succeeding sections reviewed data mining and knowledge discovery in general, and relevant work on data sonification in specific. Furthermore, this thesis set out to investigate the evolution and current practices in HCI including literature study on three waves of HCI. The concept of the third wave as a key element in this work, was reviewed in more detail. Additionally, the focus was on user centered design and user studies where requirements for a methodological design framework were derived from. These led to the development of SysSon framework. Then the design choices and components in SysSon are introduced and user studies where SysSon was used are illustrated. The two groups participated in these user studies were climate scientists from Wegener Center, and sound experts from IEM. Finally, participatory design is introduced and an interdisciplinary workshop is explored following sonification designs to investigate the quality of such interdisciplinary work. Sonification designers and climate scientists participated in this workshop and the results provided valuable insights into various aspects of knowledge transfer and sonification design practice. Two appendixes are attached to the end of this chapter. The first one described an art installation that was a result of the project in order to carry out the sonifications to the public. The second one included questionnaires and data from user studies described in this work.

The intended readers for this thesis are the sonification and auditory display community and the broader HCI research practitioners. Climate scientists and data science community in general may also benefit from reading this work. The contributions to each of these disciplines vary. The hope is that this work will impact the use of sonification and auditory displays in data analysis tools and makes it more common in everyday technology in the long term. The contribution to the display design and HCI community originates from the insights we gained from adapting the HCI design practices and concepts into sonification field using climate science as an exemplar.

The user-centred, methodological approach to sonification and the application of interdisciplinary work with climate scientists is proposed, however, is not tied to the specific domain of climate and is potentially applicable to any discipline.

This work has provided some answers to the questions it intended to investigate, but also left others open and produced some new ones. The following is an effort to emphasize some of the main issues that arose from this work and reflect on them as well as propose future lines of research. In the introduction the overall research question is described as:

How to design a systematic approach to develop sonification frameworks that facilitate the efficient use of sonification by domain scientists?

The key design methods used in this work are extracted from user centered design disciplines of HCI. Needs assessment methods such as contextual inquiry and focus groups helped to gather insights into the domain scientists needs. Furthermore, analytical methods such as workflow and task analysis outlined the way domain scientists work, think, and analyse data. Methods from the third paradigm of HCI were useful to tackle the users needs in their own context. PD methods such as interdisciplinary communication and workshop created a platform for an interdisciplinary knowledge creation and exchange. We definitely did not aim to create new hypothesis in the domain science, rather looked into alternative methods to explore and present complex data. Creating a general tool for development of sonification methods and sound creation was not the central goal, but also a side product of the work. In the process of this work by the author and the experts involved in the project several sonification design examples are created. The raw material has been reworked and attached in the project’s wiki. Creating reproducible sonification methods for data mining tasks and comparative research methods in sonification were also by-products that could be shared with Auditory Display communities (ICAD, ISON) in specific and HCI communities in general.

7.1. LIMITATIONS

Within the scope of SysSon project many compromises were necessary to be made due to time and resources constraints. One of the main barriers was the use of ScalaCollider as the programing language for sonification which was not familiar for neither the climate scientists, nor the sonification experts outside of the project. Using a scripting language that is familiar for domain scientists such as Python for prototyping could help accelerate sketching sonification design ideas. The programming language barrier also slowed down the process of preparation for workshops and collaborations which created some non optimal research results by multiple studies. Another limitation in this work was not having access to the exactly same users throughout the life cycle of the project. Because the users were not really dependent on the sonification framework for their daily workflow, we needed to find volunteers for each stage of the project which lead to a diverse group of climate scientists. The positive aspect is that therefore more climate scientists got familiar with sonification and the use of auditory display, but the disadvantage is that none of them got a deeper understanding of it to the extent to become an intermediate user who is capable of prototyping within the sonification tool.

7.2. FUTURE RESEARCH

To carry on this research field, I suggest to continue the collaboration with domain scientists through training and workshops similar to Science by Ear III to create a bigger pool of available sonification designs and prototypes. Then, comparing and using these prototypes in combination of visualization techniques to see/hear where they work together or where they are more useful. Additionally, integration of sonification into the climate scientists' workflow as a regular hack session every few months would be useful to familiarize them and to make it part of their data analysis routine. The author hopes that systematic sonification inspires researchers to develop new methods of sonification and the application of a variety of HCI methods in sonification lead to some standard which assist the data analysis workflow.

APPENDIX I: TURBULENCE

CARRYING THE SONIFICATION FRAMEWORK TO AN ART INSTALLATION

The timely issue of climate change makes the impact of SysSon project broader. This appendix describes an art installation (as a by product of the project) that aimed the outreach of the project at general public to increase their awareness.

Two different events from four different institutions came together to create the installation: a workshop named “Forecast“and the follow up exhibition “Turbulence: a climate sound portrait“. An EU funded project ADRIART (Advancing Digital and Regional Interactions in Art Teaching) offered a course “Responsive Art in the Public Realm“in an international consortium among four universities to create the visual components of the exhibit. The members of SysSon project were responsible for the audio components of the exhibit. Within these settings, our aims were to explore ways of setting the fields of interactive art and sound in dialogue with scientific data and digital technologies, while contributing to the contemporary debate on climate change with researchers, teachers and students. The goal of the workshop was to create a spatial ambience and a sensorial interface to display the sounds and to interact with them. During the workshop the students and mentors worked together to bring different components of the project to the focus. The final installation was presented in an exhibition in the Forum Stadtpark Graz.

DATA

The data used for the exhibit emanate from a climate model, and from satellite measurements:

- 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.
- 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 [Gra94], 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.

SETUP

Several pieces were come together in one and only semantics to create Turbulence: structure, sound composition, spatialization, data translation, aesthetics, and interaction. The prototype once called “float” (which was the outcome of ADRIART’s workshop) transformed into a gigantic and convoluted piece of multi-layered processes. Once the triangular frames were hanging next to the multichannel speaker system, the space started to shape the art. The sensors allocated in the middle of each of the triangles gave the first signals for the subsequent installation. Hanging by hand each of the threads with squared papers was certainly a pleasant repetitive experience; a sort of meditation in which the team became a twining organism that knitted slowly while adapting to the changing sound environment. During uncountable hours of collective work, not only the installation grew, but also an interesting conversation on aesthetics and other theoretical discussions arose. The set-up was then a platform for exchange and common decisions. The most striking aspect of the montage dynamic in such a large cooperation system is that the personal requirements of each of the components necessarily need to dissolve into a collaborative field. Turbulence was a paradigmatic example of this kind, and the work stood as a witness of dialogue between institutions and projects.

SOUND LAYERS IN THE EXHIBIT

The installation was 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 made use of different data sets:

- Soundscape: This layer corresponds to the idle state of the system and is heard when no sensors have been triggered 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.

- 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.

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

- Anomalies: This layer uses measurement data from radio occultations. 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.

- Intensity: The soundscape from the idle layer has been processed to have a flat 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.

- 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.

- 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.

- 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 come 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.

BRIEF FEEDBACK FROM THE EXHIBIT VISITORS

Three aspects were explored before and during the exhibit were:

- Collaboration between creators
- Impressions of the audience
- Interactions of the audience

To get a better understanding of these three aspects, the author conducted informal interviews with 20 visitors of the exhibit and 12 members of the collaborative project. The interactions and collaboration between different institutions and disciplines were very thrilling and at the same time challenging for all people involved. Different work styles, and the fact that the exhibit is an evolving process made the estimations and some time management issues challenging. After all, all creators were very happy with the outcome and have learnt from collaborators from different disciplines.

Interviewing the exhibit's visitors made it clear that not all the visitors were aware of the content of the exhibit even not after visiting it. This was not because of the lack of information or brochures but rather because of the style of interacting with an art exhibit. Some people just prefer to enjoy an exhibit without being disturbed with the information available. There were visitors who were more interested in exploring the space and interacting with sensors and listening to the sound without understanding the data behind it. The words the visitors described the exhibit were: enjoyable, confusing, sleepy, and relaxing.

Observing and asking the visitors we found there were three types of interactions with the sensors. Some visitors totally avoided the sensors, some were exploring them in a moderate way, and some were over-exploring the sensors. At the vernissage and finissage the third case was more common which seemed to be from mirroring other people's interaction style. In general, most visitors explored the central part of the exhibit more often than other parts of the room and they stayed there 10 to 20 minutes. The visitors could remember specific sounds, but not specific sound patterns and they couldn't relate it to any data.

INVOLVED INSTITUTIONS IN THE EXHIBIT

SOUND COMPONENTS:
IEM, University of Music and Performing Arts Graz:
Hanns Holger Rutz, Katharina Vogt, Visda Goudarzi

CLIMATE DATA EXPERTISE
Wegener Center, University of Graz: Andrea K. Steiner, Martin Jury

ADRIART – Advancing Digital and Regional
Interactions in Art Teaching | www.adriart.net
SPACE AND INTERACTION
built installation: Float
Students: Ana Sabolić, Laura Nefeli Chromecek, Liberta Mišan,
MENTORS: Daniela Brasil, Nayarí Castillo, Richard Dank

TECHNICAL ASSISTANCE
Helene Thümmel, Jacob Wegerer, Mateusz Pankiewicz, Patricia Wess

APPENDIX II: DETAILS ON USER STUDIES

This Appendix includes guidelines and questionnaires used in different user studies that are discussed in this thesis. The collection is chronologically sorted from the beginning of the project.

User study 2012 (contextual inquiry)

Needs' assessment in Climate Science
Wegener Center, May 2012
Interview guideline

Introduction:

- *Sonification*
- *SysSon project*
- *Prepare to show us a specific data task*
- *Later: listening tests*

Qualification of participants

☐Prof ☐PostDoc ☐PhD candidate ☐diploma student

☐ArsCliSys ☐ReLoClim ☐EconClim ☐other:

Years working in the field:

How often do you analyze data?
☐ every day ☐ every week ☐ every month ☐1x/year

Which tools do you use to analyze/ visualize data?

Have you had previous experience with other tools to analyze/ visualize data?

Task – walk-through, think-aloud: Problem discovery/ Needs' assessment:
Please lead us through a typical process of data analysis that

- *you had to do recently,*
- *where you were faced with (raw/ rather raw) data and wanted to understand it better, find out something about the data (successfully or not), etc.,*

- *and which you then discussed with colleagues or presented at a meeting or similar.*

☐ **Technical background**:

☐ What's data format you prefer to use? Why?

☐ Do you use raw data or do you calculate your own derived parameters?

☐ Which program(s) do you use? Why?

☐ Is there any audio playing possible at your workplace?

☐ **Scientific background:**

☐ **What** is the task? **Why** do (did) you do this task?

☐ **Explain** what you can deduce from the data! / Explain what you see in the plot!

☐ **User goals:**

☐ Is the task **entertaining** you? / Do you like this part of your job?

☐ Do you **have to** use this tool regularly?

☐ Do you usually try to end up with a **nice** plot (or other visualization) or do you simply want to understand it? (> *Task success*)

☐ Did you need to learn a lot of things before using these tools? How often do you need technical support or help to use these tools? (> *Learnability*)

☐ How do you find out that an error occurs? How do you cope with errors? (> *Errors*)

☐ Do you consider it an efficient way of completing the task? / How many steps are necessary to complete the task? Is it very complex? (> *Time-on-task, efficiency*)

Expectations, open feedback

☐ What would be an **optimal tool/ enhancement** for/of the task you showed us?

☐ When/ which was **the last new tool you learned** in the context of data analysis and visualization?

☐ Do you program your own applications?

☐ Can you **imagine using audio** for

☐ exploration (workplace) ☐ presentations ☐ anywhere (mobile application)?

... and Why? /Why not?

☐ Why would people use audio at Wegener Center? Why not?

☐ Where can **sonification help** in climate science in your opinion? Which data sets could be ideal for sonification?

☐ The example you showed us... **how could it sound like**?! (Sing/ make any sounds or explain!)

Focus Group

Please present the task results that you showed to us in the personnel interview to your colleagues.

Research Profiles

The following section describes the research focus of the researchers who participated in the contextual inquiry and focus groups.

ArsCliSys - Atmospheric Remote Sensing and Climate System Research Group
Researcher S. is PhD candidate in the ArsCliSys group. She walked us through a task, where she compared two entities. (a), the absorption loss profiles of clouds, measured by satellites (and given as intensities in HDF format, read with Python), and derived from it a simulated beam path. This path needs to be checked with measurement data. Thus (b), the ICE, ice water content, gives realistic clouds. For a set of 8 events, she visualized the two entities with Python. The result is a visual analysis, if the beam paths correspond to a cloud or not. For the subsequent simulation, it is important to model the correct quality (shape) of the cloud rather than only the correct IWC.

Researcher Z. is Junior PostDoc in the ArsCliSys group. In her task, the hypothesis to test was if the sun activity has an influence on the ionospheric residual error of radio occultation data that is not sufficiently corrected. Plotting the data for 10 years of varying sun activity supports this hypothesis. The results will be used to enhance the corrections of the simulation data.

Researcher L. is professor in the ArsCliSys group. He showed us several projects that he supervises. First, a simple collection of extreme (hot, cold, etc.) times in Graz has been done within a bachelor thesis. Weakly weather data is provided online by the university's weather station. Second, the climatologies created at WegCenter based on radio occultation data. Furthermore he reported a larger study, where local errors in measurement data of satellites was found using the WegCenter simulation data.

Researcher E. is PostDoc in the ArsCliSys group. She reported a past project, where atmospheric profile data in the tropical region was studied. In a certain height level, El Nino and El Nina phenomena have a clear signal. This results was first found visually, and then studied further statistically, using principal component analysis and multiple linear regression.

Researcher R. is diploma student in the middle of her research work in the ArsCliSys group. She optimizes (by re-writing) an algorithm that analysis temperature profiles around the world in order to find the tropopause, defined (in different approaches) according to mathematical properties of the temperature curve.

ReLoClim - Regional and Local Climate Modeling and Analysis Research Group

Researcher I. is PhD candidate in the ReLoClim group. He was part of a project, where models with wider grids were compared to fine grids – to see, if the augmented computational effort of the latter is justified. Four different regional climate models were simulated at 10km and 3km resolution. Data is provided in IDL specific format, initially checked for errors in the simulation using ncview, statistically analysed and finally plotted with the group-intern program WICE. The results show a systematic change between fine and coarse simulations, where fine simulations, e.g., have overall more precipitation (usually an overestimate) but give more accurate daily timing for this parameter.

Researcher C. is PhD candidate in the ReLoClim group. She works with regional data sets of European measurement stations that are used to evaluate corrections of model data. Problems are missing data in the measured data sets and the visualization of multi-parameter data sets. Corrections proved to work well for the mean bias. A few stations were chosen according to their extrem location (e.g., mountain vs. valley sites), and four parameters are plotted for this task, to find systematic errors. C. used R for statistics and plotting.

Researcher N. is PhD candidate in the ReLoClim group. He compared the variability of data stemming from 22 regional models, that are driven by (fewer) global climate models. Results as simple scatter plots show, that the data can be grouped according to the underlying global model. The ultimate goal is to fill up the matrix which is built up by running each regional model by each global one – without actually doing so, due to the computational effort. (Results are plotted as climate change signals, i.e., the difference of the mean value of two 30-year periods for the GAR, Greater Alpine Region.)

Researcher Y. is diploma student in the ReLoClim group, interviewed shortly before finishing his Master thesis. He evaluated global climate models, comparing them with observational data, to see if they can be used to drive local models. The analysis was on the one hand based on (very many) visualizations of model results; on the other hand, the so-called Model Performance Index serves as a multi-parameter index of model quality and allows sorting them. Overall it turned out that the multi model mean matches best the observational data.

Researcher H. is senior PostDoc in the ReLoClim group. He recently ran and checked a simulation on plausibility, to further provide the data to a colleague. The checking was based on dynamic visualization, e.g., if the diurnal pulsing was there etc.

Researcher D. is PhD candidate in the ReLoClim group. He compares the outcome of 22 climate models in 2050 in the European region, that simulate the 2-degrees-goal of CO2 reduction, and studies their effects, i.e., 25 parameters, using R. Visualization is a major problem in this analysis. He reduced dimensions by hand and using a principal component analysis, and grouped models according to their behavior in single parameters (e.g., hotter outcomes, or dryer ones).

Researcher T. is senior PostDoc in the ReLoClim group. He pursues his own simulation to produce future climate scenarios. In the course of computation, he creates plots as quick checks for plausibility, and searching for technical or physical (theoretical) errors (the latter are harder to find). Then he calculates a climate change signal, he difference between two periods, which finally serves for publishing results. One of T.s goals is to understand the correlation between different parameters better.

Usability test 2014

Introduction to SysSon framework, Wegener Center, May 2014

The following form was only for the interviewer to have a semi-structured interview. The participants were not filling it out by themselves.

Interview Nr. ____ Name: ____ Datum: _______ Zeit: _________

☐Prof ☐PostDoc ☐PhD candidate ☐diploma student

☐ArsCliSys ☐ReLoClim ☐EconClim ☐other:___________

Years in the field: __

Are you familiar with Sonification?

Did you participate in one of our previous User Experiments? If yes in both or one? Which one?

Introduction:

☐*SysSon Platform:*

- Panic and stop buttons

GENERAL

- *Please open a workspace*
- *Open the data file*
- *Are you familiar with this type of data or not?*
- *Plot the data*
- *Explore the visuals, slices, max/min, …*
- *How's the navigation in the visualization tool?*
- *Comments?*

SONIFICATION TOOL [TIME EACH TASK for learnibility and interest (how long do they like to play around with it?)]

Task0

Time:

- *Could you open the sonification0*

- *Could you drag and drop the data into it*

    - **Task – walk-through:**

    Task1
    Time:

- *Please open the sonification1 (Graz)*

- *Please change Time, and Speed and play around with it without changing the long and lat*

Task2
Time:

- *Keep sonification1 open and open a sonification2*

- *Could you cmpare the two? Anything interesting to hear?*

- *What do you realize listening to both of them*

- *Suggestions? Comments?*

- *Play around with Time and Speed*

- *Listen more*

Task3 (not for the pilot tests)
Time:

- *Create your own sonification file*

- *Chose a specific place*

Observe if they always go for the same parameters?

If they all use the same functionalities?

If they take more time because of their interest or because of usability problems?

Expectations, feedback

☐ Can you imagine using this tool in your daily work?

☐ What are some of the tasks that you could imagine this tool is going to be very useful for?

☐ What would you like to change in the tool?

☐ Comments, Suggestions ...

Science by ear workshop (questionnaires)

IEM September 2014

Pre-workshop Questionnaire: Science By Ear III Workshop

Background:

☐Climate Science ☐Sonification ☐Music or Sound Art ☐Others: :________

Which of the following words do you recognize? If you do, please explain it with your own words.

- Global Climate model
- Timbre
- Granular Synthesis
- Audification

- Geopotential Height
- Noise
- Auditory Masking
- Climate Change
- Near-Surface Air Temperature
- Sine Oscillator
- Periodicity
- Sampling
- Atmosphere
- Ensemble
- Radio Occultation
- Calibrating
- Band pass filter

What do you expect from the workshop?

What do you expect from a sonification tool?

Post workshop Questionnaire: Science By Ear III Workshop
Background:

☐ Climate Science ☐ Sonification ☐ Music or Sound Art ☐ Others: ________

Which of the following words do you recognize? If you do, please explain it with your own words.

- Climate Simulation

- Specific Humidity
- Pitch
- Parameter Mapping
- Climate projection
- Sonic Gestalt
- Sound Synthesis
- Noise
- Calibrating
- Eastward Wind
- Precipitation
- Resonance
- Sound Envelop
- CMIP5
- Ensemble
- Periodicity
- Sampling

Sonification Patches

Throughout *Science By Ear III* workshop several sonification patches are created. Here we only present a few of them. For more details and exploring more sonification patches and listening to resulting sound samples, please check out the project wiki pages: https://github.com/iem-projects/sysson/wiki

In the following example we used near surface temperature data in monthly means (one value/ month) over 156 years in the past (1850 - 2005) and 295 years in the future (2006 - 2300). The first two files include 73 latitudes, and 144 longitudes, and the second two (zonal data) with only 18 latitudes. The sonification approach for this task was parameter mapping using granular synthesis. Each grain is a random spot and resampling the data space that way.

For this task, interesting could be:

- convection areas, e.g., Monsoon areas, where temperature and precipitation are highly interacting; for the delay it is hard in monthly data

- Himalayan region could be interesting on a monthly scale; e.g., compared to UK (where it is alsways raining)

- Looking at the pr and tas plots to find an interesting region: -- strange plot - pr is given in kg per square meter per seconds; very small values, very dark; lines of long and lat not able to see -- it is difficult to find same spot in both data sets

- chosen region: 80 - 95 deg (103-109) E; 20 deg - 30 deg N (44-48)

- 1st attempt - play Himalaya with panned longitude; latitude as frequency; density is rain

- change region: perhaps larger in long and narrower in lat?

- temperature seems to be super stable in Northern India - cannot be?!!

- new region, where there is more variation in temperature AND in precipitation: Boulder, Colorado, around 40 n (29), 105 w (52)

- other regions would be better, the grid resolution is too coarse for the task in order to calibrate the sonification

```
val minPitch = 200
val maxPitch = 2000

val pitch    = pr.linlin(minPr, maxPr, minPitch, maxPitch)
val amp0     = 0.1 // pr.explin(minPr.min(1.0e-9), maxPr, 0, 1 / density)

val amp1     = amp0 * UserValue("gain", 0).kr.dbamp
val amp = amp1 * (pr > 1.0e-5)

val buf      = Buffer("grain")

val bufSize = 4096
val fund     = SampleRate.ir / bufSize
val speed    = pitch / fund

val pan      = lon.linlin(minLon, maxLon, -1, 1)

val grains   = TGrains.ar(numChannels = 2,
  trig = trig, buf = buf, speed = speed, dur = grainDur, pan = pan, amp = amp)

// val test = SinOsc.ar(pitch) * amp

output := grains
```

Parts of Sample Code from Sonification of Precipitation using Granular Synthesis

```
val side       = anom < 0  // too cold = 1, too hot = 0
val octave     = side * 2
val pitchRange = K2A.ar(UserValue("pitch-range", 12).kr)
val pitchClass = presVals.max(1.0e-10).explin(10, 100, pitchRange, 0).roundTo

val pitch = octave * 12 + 60 + pitchClass

if (PRINT) pitch.poll(trig, "pch")

val freq    = pitch.clip(12, 135).midicps
val ampCorr = AmpCompA.ar(freq)
val amp     = (anom.abs / 4) * ampCorr

val ok   = (ta \ 0) > 0
val gain = UserValue("gain", -12).kr.dbamp * ok

val osc = SinOsc.ar(freq) * amp
val sig = Mix(osc) * K2A.ar(gain)

val yearTrig = Trig1.ar(month sig_== 0, dur = SampleDur.ir)
val yearAmp  = K2A.ar(UserValue("year-pulse", 0.1).kr)
val yearSig  = Decay.ar(yearTrig, 0.1).min(1) * WhiteNoise.ar(yearAmp)

val outSig = sig + yearSig

output := Pan2.ar(outSig)  // TODO: decide panorama / stero image
```

Sample Code from Sonification of QBO (Quasi-Biannual-Oscillation) data

Computer music JF (questionnaires)

12.2014
Data:
Data from climate models projecting one possible scenario:

Time resolution:

- 2006 – 2300
- monthly means (i.e., 1 value per month), in total 3539 months

Spatial resolution:

- 144 longitudes from -177.5 (West) to 180 (East)
- 73 latitudes from -90 (South) to 90 (North)

Data parameters:

- tas - anomalies* of temperature at surface (air temperature 1 m over ground)
- pr - anomalies* of precipitation (rain, snowfall...)

*Anomalies: deviation from the mean value over the same month in 30 years (e.g., January 2030 = January 2030 – Mean(Januaries 2015-2029; Januaries 2031-2045))

The original distribution of the anomalies data (for a random time frame):
These data have been linearized with an arcus tangens function.

Sonification model:

Idea: design 4 distinct regions of data/ sound:

Granular synthesis / Mappings:

- grain pitch depends on temperature, with a gap of one octave for the tas threshold region:
  -
- grains' density and shape of envelope depends on precipitation:

SysSon Platform:

The tool has two components:

- Analysis tool
- Development Environment: editing and compiling new sonification scripts

To create a new project, you can chose Workspace, and for creating and testing ScalaCollider scripts you can chose Interpreter. For the examples we chose OpenRecent to use the existing scripts.

In the Workspace menu, you have the option of uploading a dataset, or a sonification or etc. Here we start with uploading and opening a dataset.

Plotting Interface:

This interface is used to:

- uploading data
- zooming in and out of plot
- exploring different dimensions of data by using sliders (also possible in the sonification tool)

Sonification Interface:

This is the interface we will be mostly using during the workshop. You can see that the data sets that we are going to sonify are already uploaded to the interface (pr, and tas parameters).

The sliders make selection of ranges and navigation throughout the data (e.g. locationwise: longitude, latitude, and timewise) possible. You can chose different regions and listen to them to compare if you can hear different patterns in the data.

The control section is to modify and tweak the data followed by sound. This section is what you'll be working with the most and modifying to tweak the sound.

Mute, pause, forward, speed, and playback buttons are also available to allow you to listen to the sonifications multiple times or stop them as you wish.

Task 0:

Tune the data for dummy data to have 4 different sound regions.

Task 1:

Test the parameters with real data: tune them in a way that distinctive sounds for different regions around the given coordinates appear:

- South Greenland: 45 W, 62,5 N
- Austria: 15 E, 47,5 N
- Australia: 140 E, 35 S

Task 2:
Describe what you think happens in these regions.

Task 3:
Can you hear and describe differences at the beginning and versus the end of the data set?

Task 4:
In terms of an interesting soundscape, what would you do next?
In terms of an efficient sonification, what would you do next?

Task 5 (if time):
Try to twist the program to reach a more interesting sound.

Task 6 - Feedback:

For this section we have two forms, one for the observer (one of us) in each group, and one for every participant.

Observer's questionnaire:

- How much time the group needed to get familiar with the tool and start their own tweaking?
- Did they work together and everyone contributed or one or two people were dominating the discussion and workflow?
- Did they make use of their SC knowledge?
- Did they spend more time on the GUI or on the text-based interface?

Participants' questionnaire:

- How long did you need to learn learn the tool? Was it easy to use? Please explain.

- Was the plotting tool helpful? Did you use it at all? Please explain.
- Did you use the GUI?
- Did you prefer the GUI or text-based scripts?
- Was the prepared code understandable? Could you make changes in the code easily?
- Do you have a better understanding of data/ climate system in general?
- What did you like/dislike about sounds' aesthetics, possibilities & limitations?
- Would you use the tool? Why? Why not? If yes, would you use it for data analysis or sound creation, or both?

Self-assessment of collaboration

- How would you rate the final sonification that the group put together?

  very poor 1 2 3 4 5 6 7 excellent

- Which number describes the way the group made decisions?

  very inefficient 1 2 3 4 5 6 7 very efficient

- How would you rate group member contribution to the task?

  no one contributed 1 2 3 4 5 6 7 every one did

- How do you feel about the way the group has worked?

  displeased 1 2 3 4 5 6 7 pleased

- What do you think about the group's organization during this project?

  disorganized 1 2 3 4 5 6 7 organized

- How satisfied are you with the way the group used its time?

dissatisfied 1 2 3 4 5 6 7 satisfied

- Did you learn anything about the way your colleagues work? Please explain with examples.

Online study: questionnaire

December 2015

Demographic questions:

- How old are you?

- What is your field of study/work?

- How many years of experience do you have? (excluding your undergraduate education)

- Are you familiar with music?

- If yes, for how long?

less than three years 3-5 years 5- 10 years more than 10 years

- Do you have any data analysis tasks in your job?
yes no

- If yes, what are some of the tools you use?

Sonification is the use of non speech sound to convey information. In order to answer the following questions, you don't need to know what sonification is but for your information, the following sounds are generated using data sets from climate science.

Sonification questions:

- Please listen to the following sound and say if you hear a trend in it?
yes
no

- If yes, how do you describe the trend?

- How many types of sound do you hear in it?

1 2 3 more

- Can you describe it as:

ascending descending stable

- Do you hear periodicity in sound?

- If yes, how many repetitions do you hear?

- Could you hear the number of occurrence of the noisy sound?

yes no

- if yes, how many times?

- Which of the three sounds is different from the other two? 1 2 3

- How do you describe the difference with your own words?

- Which of the three sounds is more different from the other two? 1 2 3

- How do you describe the difference with your own words?

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