4 AUDITORY DISPLAYS

Computer Science is no more about computers than astronomy is about telescopes. — E. W. Dijkstra

AUDITORY DISPLAYS are the primary area of related work in this research. They can be considered of being the auditory analog to a visual monitor and are utilized as system to *display* abstract data using auditory means. Auditory displays are employed in a variety of applications, ranging from computers and medical workstations, to information displays in aircraft cockpits and control centers in nuclear power plants. The main difference to the more commonly employed visual display is that the information is perceived solely through the sense of hearing. This opens many advantages and possibilities for the design and application of this technology, but also inflicts difficulties caused by an audio-only presentation. The goal of this chapter is to provide an overview of the techniques developed in this area and to examine their strengths and weaknesses for a later application within 3D virtual auditory environments.

A large portion of this research is directly based on 3D spatial auditory displays, therefore the first section of this chapter serves as an entry point and introduces the most fundamental concepts and techniques. Available possibilities for an audio-centered data mapping are examined in the following section, which also discusses auditory Gestalt principles, the analogic/symbolic continuum, as well as spatial sonification and data representation techniques. The last section presents several examples and areas of applications, and focusses on issues of construction, authoring and design.

4.1 OVERVIEW AND DEFINITION

The research on auditory display systems and sonification techniques accelerated with the introduction of the ICAD conference, which was held for the first time in 1992 (Kramer, 1994). However, the first publications that were concerned with an application of sound and acoustics for the display of abstract data were already published in 1954 and 1961 (Pollack and Ficks, 1954; Speeth, 1961). The article by Pollack and Ficks described a quantitative display through the use of several auditory variables. Employing tone and noise bursts, this first auditory display was able to represent eight binary variables through the use of pitch, loudness, temporal ratio, duration and stereo location (Pollack and Ficks, 1954). A second article published by Speeth in 1961 employed a technique called *audification* to sonify seismic data (Speeth, 1961). An accelerated playback of the recorded seismic waves greatly improved their analysis and understanding.

The term *Auditory Display* has not yet been conclusively defined, but was coined and influenced by several ICAD conferences and the foundation of a research community:

> *"Auditory Display research applies the ways we use sound in everyday life to the human/machine interface and extends these via technology. The function of an auditory display is to help a user monitor and comprehend whatever it is that the sound output represents." (Kramer, 1994; ICAD Community, 1992 - 2008)*

A second and very similar definition was provided later by Hermann in 2006:

> *"Auditory Displays are systems where a human user makes sense of data using his/her listening skills, like for instance any data under analysis or data that represent states of the information processing system." (Hermann, 2006)*

Both definitions concentrate on the user's ability to identify and interpret auditory signals and the development of audio-based human/machine interfaces through the sonification of arbitrary (scientific) data. The research is founded in an interaction with sound in real-world scenarios and strives to design information processing systems that map abstract data values onto auditory variables, which in turn can be interpreted and analyzed by a human listener.

The research of auditory displays can also benefit from an analysis and observation of the interaction with visual systems. Although visual and auditory displays seem on a first glance to be very distinct, yet they share many concepts and principles. The primary difference is that an auditory perception is linear in time, ie. (3D) sounds exist in time but are perceived over space, while a visual perception is linear in space, ie. visual objects exist in space but are perceived over time. Despite these differences in perception, the interpretation and analysis of data and information is very similar. The basic principles inherent in a *good* visualization can directly be applied to an acoustic presentation of information using an auditory display as well (Schumann and Müller, 2000).

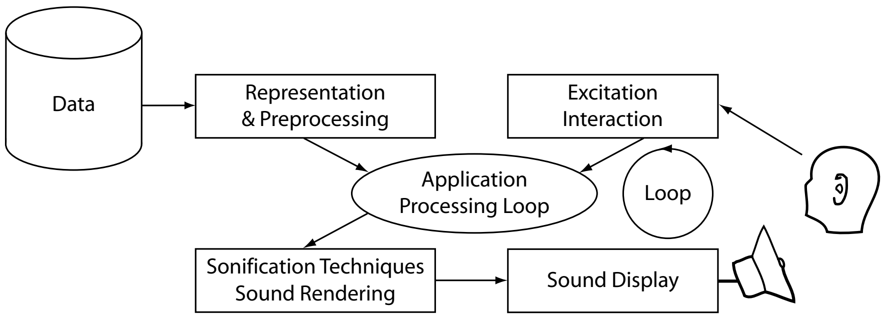


Figure 16: Auditory Display Interaction Loop (Hermann, 2006).

An overview of the principles characterizing an auditory display system can be seen in Figure 16 (Hermann, 2006). The overall layout is very similar to the visualization pipeline as presented in Figure 4. Based on the input of raw data, first a pre-processing is required to map acoustic primitives to certain aspects within the data. The user interacts with the system using an interaction/feedback loop to present specific parts of the data, or to focus on certain details. The information is then sonified and presented acoustically using the system's effectors. A single or stereo speaker setup is often sufficient, while 3D auditory displays require a presentation via headphones or the use of a large multi-channel speaker array, such as (5.1) surround sound systems (Boer, 2002b). These systems often employ cross-talk cancelation for a binaural display, as well as channel-blending techniques to improve the localization of virtual sound sources.

Key components of an auditory display framework are the sonification and interaction techniques used. Sonification can be thought of as being the auditory analog to graphics-based visualization and is defined by Kramer et al. and Hermann similarly as:

> *"Sonification is the use of sound - mainly non-speech audio signals - for representing or displaying data. Similar to scientific visualization, sonification aims at enabling human listeners to make use of their highly-developed perceptual skills (in this case listening skills) for making sense of the data. More specifically, sonification refers to the technique used to create a sound signal in a systematic, well defined way, that involves data under examination as an essential ingredient for sound computing." (Kramer et al., 1997; Hermann, 2006)*

Benefits of Auditory Displays:	Difficulties with Auditory Displays:
• Eyes free application	• Low resolution of variables
• Rapid detection	• Limited spatial precision
• Alerting	• Lack of absolute values
• Orienting	• Lack of orthogonality
• Backgrounding of tasks	• Annoyance
• Parallel listening	• Interference with speech
• High dimensionality	• Not bound by line-of-sight
• High temporal resolution	• Absence of persistence
• Affective response	• No printouts
• Auditory Gestalt formation	• User limitations

Table 1: Benefits and Difficulties for using Auditory Display Systems (Kramer, 1994).

Both acknowledge the connection between sonification and interaction to define an active sonification technique, in which the user explores specific parts of the data or information, which is in turn sonified – eg. acoustically represented (Hermann, 2002). A selection of adequate techniques for the sonification of data is one of the critical aspects in the design of an auditory display system. It includes the mapping of data attributes onto auditory primitives, which is highly dependent on the data used and the area of application. Generally, auditory displays are very applicable for monitoring tasks and for the exploration and analysis of linear data sets. Monitoring tasks are applicable, as one is listening for certain patterns to emerge that acoustically *pop out* from the auditory display (Smith et al., 1992). This exhibits one of the main advantages of auditory displays, as monitoring, or template matching tasks, can easily be performed in the background with other – possibly visually engaged – tasks at full attention. Data exploration and analysis, however, can not be backgrounded and requires the undivided attention of the listener. In these cases, one explores data sets and information, searching for certain characteristics. Although this approach requires a template matching approach as well, yet one can not precisely anticipate what will be heard.

Table 1 shows an overview of the advantages, as well as the difficulties for using auditory display systems (Kramer, 1994; Shilling and Shinn-Cunningham, 2002). One of the most important benefits is the non-necessity of paying direct attention, but also the parallel listening and the high dimensionality / temporal resolution that can be achieved are significant. Interesting to note is that the resources required for the development of an auditory display are far below the requirements for an equally designed graphics-based visualization system. Major difficulties for the use of auditory displays are a low precision, as well as the lack of absolute values. The majority of auditory parameters are not perceptually independent. This lack of orthogonality can influence the perception of a certain parameter if a second one is altered. Auditory displays are sometimes combined with a graphics-based visualization system. Such multivariate and acoustically enhanced displays generally improve the perception and understanding of the data presented through an intermodal correlation that results in a higher realism and increases the efficiency of the system.

4.2 FUNDAMENTALS AND PRINCIPLES

After this short introduction of auditory displays, the remaining sections in this chapter further explore the fundamentals in the design, as well as exemplarily discuss areas of applications. The following section continues the discussions of Section 3.2 and introduces important data and information sonification techniques. Although the section aims at a broad presentation, a slight focus is found in the discussion of spatial auditory displays and 3D sonification and interaction techniques.

4.2.1 *Auditory Gestalt and Presentation*

Examples for auditory Gestalt.

The concept of *Gestalt* refers to a unified interpretation of sensory information that is perceived in the form of patterns and interpreted in a way that the sum is greater than its parts. The original concept is based on the research of Mach and von Ehrenfels, and although it originates in the discussions of audio and music perception, the concept of Gestalt is most commonly known for its visual examples (Mach, 1886; von Ehrenfels, 1890; Goldstein, 2007). With the introduction of computer-aided sound synthesis and the development of auditory displays, Gestalt theory becomes applicable again to the perception of sound and music (Moore, 1989; Bregman, 1990; Williams). Through the perception of auditory (respective visual) information, the data perceived is analyzed, ordered and grouped regarding seven basic principles: *similarity, proximity, good continuation, habitat or familiarity, belongingness, common fate* and *closure* (Bregman, 1990; Purwins et al., 2000).

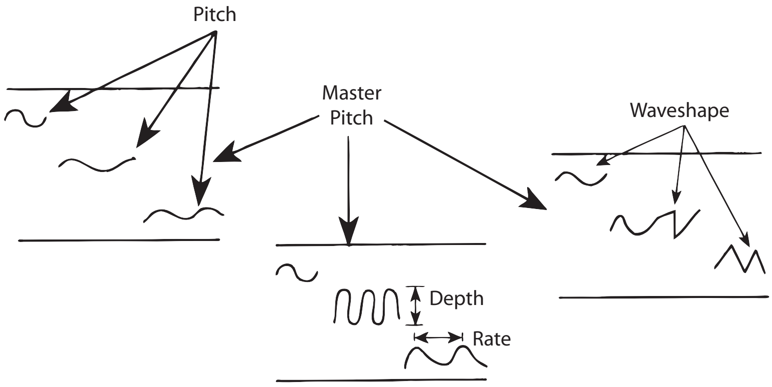
All seven principles are based on a certain grouping and classification of the information perceived. *Proximity*, for instance, refers to an auditory distance of features that groups objects with a smaller distance closer together and separates them from other elements. *Similarity* is very much alike proximity, but refers here to the inherent qualities of a sound object. The principle of *Continuation* extends proximity over time and classifies smoothly varying frequencies of a changing sound source. Sudden changes in the perception are identified as a new source. *Closure* completes perceived fragments features within the *Good Gestalt* principle, while *Common Fate* groups frequency components, that possess a similar sound or in which parameter changes occur synchronously.

The perception of Gestalt information allows one to discern overall relationships and trends within the presented data and enables a listener to pick out meaningful events within several data streams (Bregman, 1990; Purwins et al., 2000). This is a very important feature for the design of sonification techniques and important for the mapping of data onto auditory primitives.

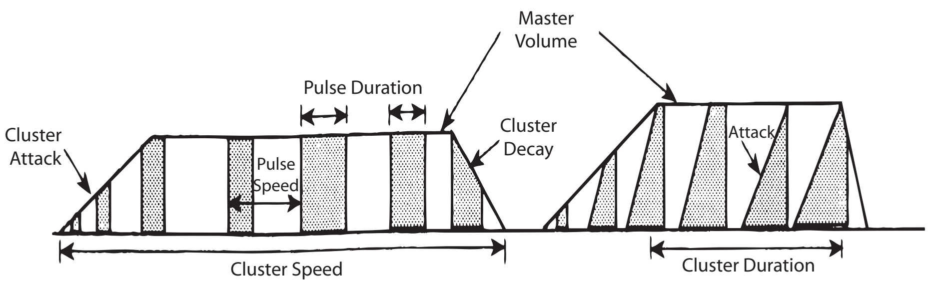
Principles of organizing sounds and the delivery of specific information through sound and sonification have also been discussed by Ballas and Kramer (Ballas, 1992; Kramer, 1992). Ballas provides an initial overview of how sound can be used to deliver information using a framework of linguistic analogies (Ballas, 1992). He identifies the main challenges for a sonification design as:

> *"to capitalize on the extensive understanding of sound production and perception in the fields of language, music and acoustics to invent new sounds that communicate from abstract sources and domains to a listener who has a complex but fixed receiving and interpretation capability." (Ballas, 1992)*

Kramer focusses more on the concepts of auditory Gestalt and devises sound organizing principles using the nesting of loudness and pitch parameters (Kramer, 1992), refer also to Figure 17. A nesting of parameters allows the control of a single auditory variable over several time scales simultaneously, thus enables the display of high-dimensional



(a) Pitch Nesting.



(b) Loudness Nesting.

Figure 17: Parameter Nesting (Kramer, 1992).

data sets. Figure 17 shows examples for the nesting of loudness and pitch, which are composed of sounds of different time scales that differ in loudness and pitch. This allows the creation of complex auditory earcons, similar to the design of 3D glyphs used in a graphics-based 3D visualization, to represent high-dimensional data sets, such as the sonification of multiple stock data sets (Kramer, 1992; Schumann and Müller, 2000).

Sonification of Stock Market Data.

Another topic in auditory perception is attention and the actual process of listening. This is described by the *Figure/Ground Problem* and refers to a selective listening process, in which one concentrates on specific parts of a possibly complex sound. Williams define this as an analytic vs. a synthetic listening:

> *"Synthetic perception takes place when the information presented is interpreted as generally as possibly, as for example, hearing a room full of voices, or listening to the overall effect of a piece of music.*
> *Analytic perception takes place when the information is used to identify the components of the scene to finer levels, for instance, listening to a particular utterance in the crowded room or tracking one instrument in an orchestral piece or identifying the components of a particular musical chord." (Williams)*

This analytic/synthetic perception is very important for the development of auditory displays and the design of sonification techniques. Depending on the sonification goal, either an analytic (concentrating on a part), or a synthetic (concentrating on the whole) presentation is required, which influences not only the overall presentation, but also the interaction with the system.

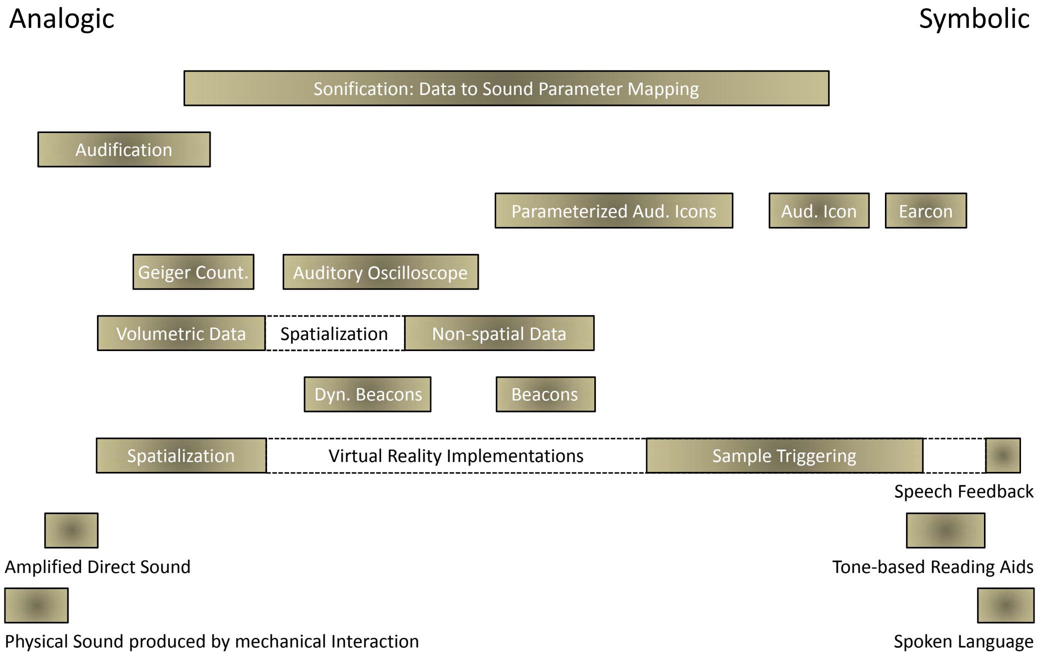


Figure 18: The analogic/symbolic Continuum (Kramer, 1994).

4.2.2 *The Analogic — Symbolic Continuum*

For a better understanding of auditory display systems and a classification of the sonification techniques available, Kramer devised the *Analogic — Symbolic Continuum*, along which all sonification techniques are arranged:

> *"A symbolic representation categorically denotes the thing being represented, while the analogic representation directly displays relationship. An analogic representation is one in which there is an immediate and intrinsic correspondence between the sort of structure being represented and the representation medium. By symbolic representation we refer to those display schemes in which the representation involves an amalgamation of the information represented into discrete elements and the establishment of a relationship between information conveying elements that does not reflect intrinsic relationships between elements of what is being represented." (Kramer, 1994)*

The concept was developed in continuation of the work of Sloman, who discussed analogic representations and their differences regarding a *Fregean*, or symbolic, information representation (Kramer, 1994; Sloman, 1971). Figure 18 provides on overview of the continuum and shows the classification of several sonification techniques. The common Geiger counter, which uses a pulse-based representation to identify radiation rates, is classified as an analogic technique, as it directly corresponds to what is being represented (Rutherford and Geiger, 1908). An acoustic alarm, on the other hand, denotes a possibly complex event or family of events, and is therefore a symbolic representation. The classification of sonification methods in terms of analogic and symbolic becomes later very important for the development of 3D scene sonification techniques to acoustically represent 3D scene and 3D object information.

Figure 18 identifies the position and the range of several important auditory display techniques. *Audification* is one of the most direct representations, in which the data is simply mapped to sound and played back. An example is the work by Heyward, who utilizes this technique for a highly analogic representation of recorded seismograms (Heyward, 1992), refer also to Section 4.3. *Auditory Icons*, which were initially described by Gaver, are very often employed and used in a large variety of sonification tasks. Auditory icons acoustically describe the thing being represented using an auditory caricature of the task (Gaver, 1989; Mynatt, 1992). An example of such an auditory icon is the sound of crumpling paper for the deletion of files and data in a computer trash can. A second example can be seen in Table 2. Cohern employs auditory symbols and familiar sounds to describe and characterize a computer's performance using discrete auditory events (Cohern, 1992).

Event	Message
Login	Knock-Knock
Connection Reminder	"Ahem..."
Low % CPU Time	Slow Walking
Low/Medium % CPU Time	Medium Walking
Medium % CPU Time	Fast Walking
Medium/High % CPU Time	Jogging
High % CPU Time	Running
Logout	Door Slam

Table 2: Event to Message Mapping (Cohern, 1992).

A further extension towards a symbolic representation is the *Earcons* approach that was introduced by Blattner et al.. Earcons possess a language-like characteristic, and are – when learned – very efficient and easy to use to identify very specific items or events (Blattner et al., 1989). Their complexity and design is parallel to visual icons and is composed of basic building blocks to describe complex structures.

An extension to this concept was later introduced by Bölke and Gorny, who established the term *Hearcons* for spatialized auditory icons and earcons. Hearcons are characterized through the four parameters: sound, loudness, position and extent, and were initially employed for an interaction of visually impaired users with a computer system (Bölke and Gorny, 1995).

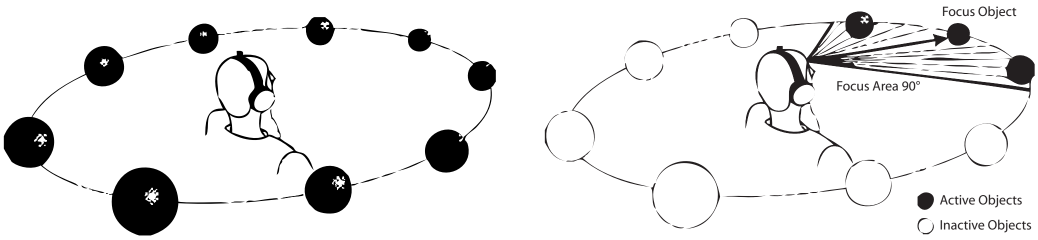
Beacons and dynamic Beacons.

Beacons, and especially dynamic beacons, characterize a more analogic representation of an analog-to-symbol conversion (Kramer, 1992). A beacon employs Gestalt information when a snapshot of the auditory data representation is performed. A dynamic beacon that is learned and intuitively understood, functions as a symbol of the event that it describes.

While some of these techniques directly display the underlying information, such as audification, others utilize auditory symbols that must be learned. Once these symbols are learned and directly understood, a link between the data and their sonic representation has been formed and the analogic display becomes symbolic.

4.2.3 *Spatial Auditory Displays*

With the assistance of sound spatialization, the advantages of a symbolic and an analogic representation can be combined. Similar to the analogic representation of visual objects



(a) The complete Menu. (b) A Selection.

Figure 19: Ring-based Auditory User Interface (Crispien and Fellbaum, 1996).

and symbols in 2D/3D space, sounds can be spatialized and assigned a certain location within a 3D environment, therefore:

> *"spatialized sound can, with limitations, be used to analogically represent three-dimensional volumetric data. The exploitation of this analogy is perhaps the greatest power of spatialized sound, in that it presents spatially indexed data in a way that is highly intuitive and, therefore, instantly understood." (Kramer, 1994)*

Sound spatialization is therefore highly applicable to represent spatial data, such as 3D volumetric data sets, but can also be employed to identify the position of objects in 3D virtual auditory environments. In here, 3D sound spatialization denotes the position of an object, while the sound itself describes its function. A second advantage of sound spatialization is an enhanced stream segregation for a parallel listening approach. This allows, through an analogic/synthetic listening process, the presentation and perception of multiple data streams as one, or a focussed listening to a single source.

Examples for spatial auditory displays include tele-robotic control, aeronautical displays and shuttle launch communications, as well as 3D user interfaces and 3D virtual auditory environments (Wenzel, 1992; Crispien and Fellbaum, 1996; Begault, 1994). An air traffic collision avoidance system (TCAS) discussed by Begault illustrates the symbolic/analogic nature of the display, as it directly correlates *virtual* 3D sound sources with their respective objects in the real environment (Begault, 1994). As of this spatial representation of information, 3D auditory displays require also spatial interactions and a 3D audio-centered user interface (Wenzel, 1992; Crispien and Fellbaum, 1996). Figure 19 shows exemplarily a 3D auditory ring-based menu system that is centered around the user (Crispien and Fellbaum, 1996). Through sound spatialization, the individual menu items are perceived as distinct sound sources, with which one can interact to make selections and changes, refer Figure 19b. Such menu systems can also be nested and layered, eg. extend over different layers in space and time, which allows the design of highly complex systems. Sound spatialization is also often employed in audio-only and audio/visual computer games to improve the user's orientation and to increase the degree of realism (Menshikov, 2003; van Tol and Huiberts, 2006), see also Section 3.4.

Demonstration of the TCAS System.

Sound spatialization is a key component in this research whose importance can not be underestimated. Combined with an intuitive and flexible 3D interaction design, it is employed in the majority of applications and example scenarios. Here Chapter 5, and especially Section 5.3, concentrate on the design of intuitive and comprehensive data and 3D scene sonification techniques using 3D sound spatialization.

After these reviews of the principles of auditory display systems and the fundamentals in auditory perception, the following part presents example implementations and discusses areas of application for auditory display systems.

4.3 AREAS OF APPLICATION

The above discussions already displayed the versatile nature and the many applications for 2D and 3D auditory displays. This concluding section summarizes the main principles and exemplarily evaluates case studies and areas of application. The majority of applications for auditory displays reside in the areas of task monitoring and auditory data analysis and exploration. However, the possibilities of representing abstract data and information solely using the means of sound and acoustics is also well known in the artistic community, which employs sonification techniques to acoustically describe stock market data, to sonify measurements of ocean buoys and to represent soundscapes of urban environments (Gaye et al., 2003; Janata and Childs, 2004; Polli, 2004; Polly, 2003). The example sonifies the top of the atmosphere at the northernmost point of a storm model and indicates strong changes in the winds. These projects are based on a sensory input and measured scientific data sets, which are mapped onto acoustic primitives and sonified for exploration and analysis, but also for pure enjoyment.

Atmospheric Weather/Works.

With the availability of efficient, yet inexpensive mobile platforms, several stationary auditory display systems migrate towards an augmented and mixed reality application. They are employed in edutainment and guiding applications, but also to develop an audio-delivered ambient intelligence (Eckel, 2001a; Sennheiser, 2008). In the Listen project, presented by Eckel, an interactive augmented auditory display is devised that provides users with intuitive access to personalized and situated audio information spaces while they naturally explore everyday environments (Eckel, 2001a,b). A direct classification of these displays is difficult, but they are most strongly related to spatial auditory user interface. Kobayashi and Schmandt and Ishii et al. have both developed a system that, in analogy to Figure 19, positions sounds and information in 3D space around the user's head (Kobayashi and Schmandt, 1997; Ishii et al., 1998). The user is thereby free in the interaction and decides what information is most important. A similar approach was later chosen by Holland and Morse, who designed an audio-based user interface for operating the Global Positioning System (GPS). The interface is designed in a way that it allows mobile computer users to perform localization tasks, while their eyes, hands and attention are otherwisely engaged (Holland and Morse, 2001). The often occurring front/back confusions of spatialized sound sources were overcome through an additional muffling and low-pass filtering of sounds positioned in the rear.

The following four sections briefly highlight some of the most important areas of application, of which some are directly related to the later introduced sonification and interaction techniques for the exploration of 3D virtual/augmented auditory environments. Audiogames resemble a special case of entertainment-related auditory display systems. An overview was provided and discussed in Section 3.4.

4.3.1 *Monitoring Applications*

The task of a monitoring application is to simply identify and display changes that are occurring within a system. Therefore, the application searches for a certain pattern in the raw data set, which, if found, is sonified accordingly. Common examples for monitoring applications are a medical heart monitor and a Geiger counter, but also financial trading and stock market data sonifications (Kramer, 1992; Fitch1992 and Kramer, 1992). All examples employ a very direct audification and display of the underlying data. The advantages for using auditory displays in a monitoring task is that the display of information is performed *eyes-free* and can easily be backgrounded, thus allowing to direct one's attention to other – possibly visual – tasks (Cohern, 1992).

4.3.2 *Data Exploration and Analysis*

An auditory data exploration and analysis requires sonification techniques for an analytic listening and presentation. Similar to monitoring applications discussed in the previous section, data exploration and analysis is based on a template matching, in which the user acoustically explores the data using a data-to-sound mapping approach. The main difference to monitoring is that one can not precisely anticipate what will be heard. Therefore, an interactive user interface is required that allows access to data scaling, routing, processing, selecting, analysis and other operations. To find significant signatures and features in a data set, exploratory techniques are employed, which might, in turn, result in the design of an optimal display system for a later monitoring task.

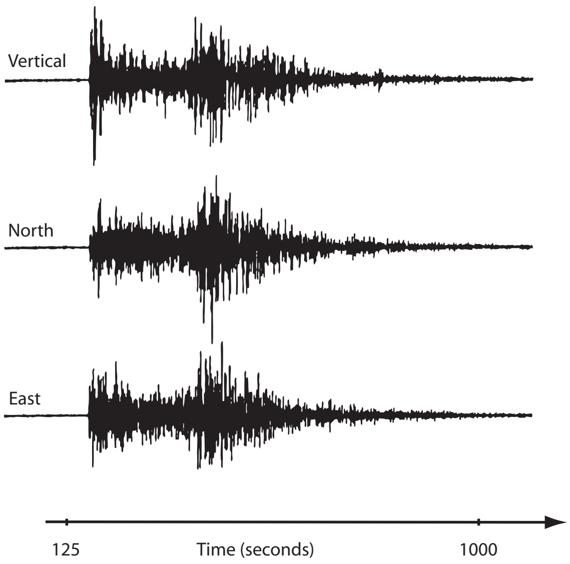


Figure 20: Three Component Seismogram of a nucular Explosion at NTS (Recorded at Lajitas, Texas, USA) (Heyward, 1992).

Audifications of Earthquakes and Explosions.

Applications for data exploration and analysis using auditory displays are in the areas of census, environmental, math, physics, geography, and many more (Kramer, 1994; Blattner et al., 1992; McCabe and Rangwalla, 1992). Heyward uses audification for the display of seismic data (Heyward, 1992), see also Figure 20, which shows three seismograms that can directly be audified. An analysis of these seismograms is often used in oil and coal explorations to find new resources. Auditory displays are not only applicable for statistical analysis of complex multi-dimensional data sets, such as for studying census and environmental data (Scaleety and Craig, 1991; Madhyastha and Reed, 1992), but also to explore physical and mathematical simulations (Rabenhorst et al., 1990; Kramer and Ellison, 1991; Mayer-Kress et al., 1992). Rabenhorst et al. present a system for the complementary visualization and sonification of multi-dimensional data sets, and describe the advantages of such a system (Rabenhorst et al., 1990).

4.3.3 *Auditory User Interfaces*

Important for all implementations is the integration of an auditory user interface (AUI) that allows the user to interact with the system and to perform changes and adjustments. An advantage of an audio-based user interface is that the area of interaction is not limited to the space in front of the user, but can be arranged 360° around the listener (Crispien and Fellbaum, 1996). This allows an interaction using a ring-based metaphor, as it was already discussed and is pictured in Figure 19. Along this ring menu system, several auditory widgets can be aligned, such as auditory sliders, buttons, checkboxes and more. Mynatt developed an auditory extension for an existing windows-based graphical user interface to evaluate the possibilities and advantages of an AUI (Mynatt, 1992). She experimented with several acoustic parameters to convey the content of the interface system and evaluated the results through an informal user study. The evaluation revealed that several of the parameters have to be enhanced and exaggerated, in order to be perceived properly (Mynatt, 1992; Brewster et al., 1992). Additionally, and in continuation of the work of Kramer, Mynatt is nesting symbols within symbols to acoustically represent different states of a button (Kramer, 1992; Mynatt, 1992). This approach can be described as a first implementation of a so called *Auditory Texture*, which will be discussed in more detail in Section 5.3.

Several Earons for a Paint Application.

3D Menu Example.

Other examples for auditory user interfaces include the sonic enhancements for two dimensional graphical displays by Blattner et al., as well as the 3D spatial interfaces for dynamic soundscapes from Kobayashi and Schmandt and the ambientRoom by Ishii et al. (Blattner et al., 1992; Gaver, 1992; Kobayashi and Schmandt, 1997; Ishii et al., 1998). The last two examples already employ spatialized sound sources to represent a real 3D user interface.

4.3.4 *Assistive Technologies*

Visually impaired people have developed certain skills to rely on auditory information alone for a navigation and orientation in the real world. This orientation is based on familiar sounds, slight vibrations and the personal experiences developed over the years. Many tools have been developed in the last decades to aid the navigation and orientation of the blind community. Some of them use the global positioning system (GPS) in combination with virtual maps and a speech processor to identify personal locations and to sonify interesting and important points nearby (Frauenberger and Noisternig, 2003a; Strothotte et al., 1995).

However, these techniques are not only applicable for guiding the visually impaired, but can also be employed to assist sighted users in visually demanding tasks, such as driving or the operation of complex machines. Several of the previous publications focus explicitly on aiding the visually impaired, while the majority of applications focus on both user groups. Nevertheless, several projects, especially in the domain of audio-only computer games, were only initialized due to requests of blind players (Warp, 1999). Much of the research in this thesis, although it was not focussing on the visually impaired, can be applied towards the development of assistive technologies. Some of the prototypes have already been evaluated and tested by several blind users, refer to Chapter 9.

4.4 SUMMARY

After this short analysis of auditory display techniques and a more detailed discussion of the important fundamentals in auditory perception, the following Chapter 5 continues to explore 3D auditory display systems with the focus on designing 3D virtual auditory environments. Several of the here introduced sonification techniques will be studied in more detail in the following chapter, as well as extended and applied for the sonification of regular 2D/3D data sets and for 3D scene auralization. By looking at the examples discussed over the last two chapters, one easily recognizes a vast applicability and a high potential for sound and acoustics. Some of these examples are further studied in the following chapters and reevaluated for an application within 3D virtual auditory environments.