How Data Sound: Sonification in Artistic Context

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Masters of Arts

in

Music

Department of Digital Humanities

University of Alberta

Abstract

This thesis investigates the use of sonification—transforming data into auditory representations—as an innovative approach to data interpretation within the Digital Humanities. As data continues to grow in complexity and volume, traditional methods of visualization are often insufficient to fully grasp the underlying patterns and insights. Sonification presents a promising alternative by providing an auditory dimension that not only complements visual analysis but also offers new avenues for understanding and engagement. This research-creation project focuses on sonification art, an arts practice that translates data from observations of real-world phenomena into musical parameters using mapping methods, with sound as a key medium for expression. By developing a comprehensive framework for sonification in artistic contexts, this thesis aims to bridge the gap between art, science, and technology. The project employs parameter mapping and algorithm development to translate various data dimensions into sound, creating a portfolio of sonified artworks that demonstrates the capability of auditory representations to uncover hidden patterns in a dataset and enrich data analysis. Through this interdisciplinary approach, this thesis contributes to the field of Digital Humanities by advancing the understanding of data representation and expanding the possibilities of artistic expression. By combining auditory and visual data representations, the project seeks to inspire new forms of creative exploration and dialogue, pushing the boundaries of how data can be perceived and utilized. The outcomes highlight the transformative potential of sonification in enhancing both the interpretative and aesthetic dimensions of data, emphasizing its role in fostering innovation and collaboration across diverse domains.

Dedication

In loving memory of Karin, whose last words to me echoed:

“I will not go down without a fight!"

I love you, and I miss you dearly.

Your Ninzy, always.

Acknowledgments

I would like to extend my deepest gratitude to my supervisor, Dr. Scott Smallwood, for his support, guidance, and encouragement throughout this journey.

I am also grateful to my committee members, Dr. Brian Fauteux and Dr. Marilene Oliver, for their constructive feedback, and thoughtful suggestions.

A special thanks to Dr. Daniel Laforest, the Area Coordinator, and Nicola DiNicola, the Graduate Advisor of the Digital Humanities Program. Their support has been crucial throughout my academic journey.

I would also like to extend my gratitude to Dr. Harvey Quamen for his outstanding teaching of digital humanities techniques. The knowledge I gained from his courses has been invaluable to my learning and academic growth.

I am deeply thankful to my family and friends for their unwavering love, patience, and encouragement. Their support has been my anchor during challenging times.

I would also like to express my gratitude to the Digital Scholarship Centre and the Sound Studies Institute for providing the venue and support for my exhibitions, performances, and workshops. Their resources and assistance have greatly enriched my research experience.

Lastly, I extend my appreciation to all those who have supported me in various ways throughout this process. Your contributions have been invaluable, and I am deeply thankful for your support.

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1.1.1: Motivation

As a contemporary composer and sound artist, I am fascinated by the audiovisual transformation of data through digital technology. Specifically, I am interested in how artistic reinterpretation can offer new insights into the analysis of scientific data via sound art, especially when created collaboratively with other artistic disciplines, thereby broadening the scope of interpretation. Recently, there has been an increasing interest among artists, including media artists, musicians, and sound artists, in producing data-driven artworks that seamlessly combine sound and visual elements. My personal motivation and methodological approach as an artist are significantly shaped by this convergence of art within the context of the humanities.

It might be common knowledge that data are indispensable across various fields such as science, politics, economics, and daily activities. In all these areas, data underpin many decision-making processes. The volume of data continues to grow due to the progress in information technology and the perceived potential of data utilization. While data can include straightforward and well-documented information, it is often believed that data also contain implicit or concealed insights into the phenomena being studied. For me as an artist-researcher, the challenge of uncovering these hidden insights is particularly appealing.

Two prevalent methodologies exist for deriving fresh perspectives from data: statistical examination and data interpretation, both of which aim to render data characteristics perceptible to human senses. The interpretation of data garners significant attention from both scientific and humanistic perspectives. Nonetheless, it predominantly relies on visual modalities for various reasons.[1] However, sound is commonly incorporated into these frameworks as an additional element, typically aimed at enhancing immersion and emotional engagement, sometimes drawing inspiration from cinematic methods.

Sonification, the process of translating data into auditory representations, presents a promising avenue that can offer a valuable alternative to, and departure from, traditional visualization techniques. However, despite its potential, sonification has yet to attain the same widespread acceptance as visualization. This premise serves as the foundation for the research-creation thesis presented here. Additionally, I posit that it is not only scientists who are captivated by the role of data in contemporary societies; artists have consistently contributed to societal dialogues, with media artists, musicians, and sound artists increasingly demonstrating interest in crafting artworks that interpret data in aesthetically engaging manners. This aspect significantly informs my personal drive for undertaking this thesis project.

1.1.2: Sound in Digital Humanities

Digital Humanities (DH) emerges as an interdisciplinary and collaborative domain positioned at the intersection of digital computing technologies and humanities disciplines. It involves integrating digitized or born-digital materials and techniques from diverse areas such as art, ~~art~~ history, archaeology, cultural studies, literary criticism, philology, among others, with computational tools like data mining, visualization, digital mapping, publishing, information retrieval, and statistics. DH encompasses a broad spectrum of practices, including analysis, coding, curation, criticism, database management, digitization, document examination, geographical information systems, multimedia publication, pedagogy, project administration, text encoding, processing, and visualization. The outcomes of DH methodologies significantly influence various aspects such as creation, dissemination, preservation, research, and education[2].

[1] Factors such as accessibility, established scientific practices, the convenience of print publication, and various additional considerations.

[2] Barber, J. F., 2016.

Historically, scholars in Digital Humanities have extensively examined advancements in film and television, highlighting the ability to provide commentary alongside or within visual media in real-time. However, a comparable exploration of sound has gained traction only since the launch of SoundCloud in 2007. As sound-related tools have become more accessible, innovations such as looping audio files, adjusting volume, tagging, commenting, annotating, close listening, and comparing different channel formats have significantly broadened the scope for sound-focused scholarship[3].

For example, Annie Murray and Jared Wiercinski underscore the significance of listening and annotation for digital humanities scholars involved in literary criticism of poetry sound recordings. They propose a methodology for developing a web-based sound archive specifically designed for literary criticism, highlighting features that support this type of analysis[4].

Despite the groundbreaking work undertaken, Allison Whitney argues that Digital Humanities (DH) research tends to prioritize visual components—such as images, animation, video, and text presented visually—while often overlooking the potential of auditory elements. Imagining the capacity to analyze voice dialects through integrated sound files, employing speech sounds to delineate research parameters, or utilizing sound for the examination of intricate data introduces innovative avenues for sonic artifacts such as soundscapes, sound maps, sound collages, and remixes. These possibilities can manifest in diverse formats, including digital narratives, oral histories, curated displays, installations, performances, broadcasts, or as independent entities like embedded sound, podcasts, internet radio, archives, and curated compilations.

This research-creation thesis aims to incorporate sound into the field of digital humanities by linking data exploration with artistic expression. By employing sonification techniques, it acoustically represents data, offering an engaging alternative and complement to the traditional visual methods prevalent in data interpretation. Like data visualization, sonification inherently

[3] Sterne, J., 2011.

[4] Murray, A. and Wiercinski, J., 2014.

fosters interdisciplinary approaches across art, science, and technology, merging data domains with digital humanities and sound studies methodologies.

1.2: Literature Review: Understanding Sonification and Its Significance

1.2.1: Data, Information, and Knowledge: Key Differences

Sonification involves generating sound as a response to data and interactions. To grasp this concept fully, it's crucial to distinguish between data, information, and knowledge. Data represents measurements of changes in a phenomenon that exist independently of our awareness. For example, contemporary weather monitoring systems generate extensive weather data globally, depicting environmental changes understandable to humans, whether through direct sensory observation or technological means, even if not actively monitored.

Upon examination, raw data transitions into comprehensible information. By careful examination, we extract precise particulars like temperature, humidity levels, or the degree of cloud coverage. Additionally, if we hold pertinent prior knowledge that aligns with the recently acquired information, we can use this familiarity to draw informed observations and conclusions. For instance, we might predict if the weather will be hot, prompting us to dress lightly or pack accordingly, or if rain is likely, prompting us to carry an umbrella.

1.2.2: Auditory Perception in Data Exploration

In the realm of data perception, our natural tendency often leads us to rely on visual representations, such as charts or bar graphs. However, visualization has some limitations, despite the impressive capabilities of human vision, it does not offer a complete solution. In contrast to vision, one notable advantage of human hearing lies in its capacity to consciously process a much higher data resolution per second. Consider the scenario of engaging in a fastpaced video game, a widely popular activity heavily dependent on time-sensitive visual cues. Typically, we are content with 60 frames per second (FPS) in video quality. A decrease from 60 to 59 frames usually goes unnoticed and does not significantly impact our overall experience. This is markedly different from sound, where even the older compact disc (CD) quality provides 44,100 data points per second. While we may not individually perceive every subtle data point, the collective information, when combined with adjacent data points, enables even an untrained ear to detect changes in pitch, tone quality, volume, and spatial location. Importantly, a sound impulse lasting 1/44,100th of a second is readily recognized as a simple 'click.'

1.2.3: The Auditory Characteristics of Sound[5]

During the process of auditory perception, individuals typically identify various attributes such as pitch, volume, timbre or tone quality, duration, and the spatial positioning of the sound relative to oneself. These dimensions reflect psychoacoustic interpretations of the acoustic characteristics of the sound.

The primary frequency, defined as the frequency of repetition of a periodic waveform per second and measured in hertz (Hz), serves as the basis for our perception of pitch in acoustics. Loudness, on the other hand, is determined by the amplitude of the sound waveform, with greater amplitudes corresponding to louder sounds. Every sound we encounter comprises a combination of multiple distinct frequencies, each with varying levels of loudness, resulting in a distinctive timbre or tone color. This is why a note A3 produced by a violin and a piano, despite sharing the same primary pitch, possesses unique and discernible qualities.

Another implicit attribute associated with sound is its duration, which refers broadly to its temporal aspect. Substantial alterations in duration have the potential to impact other characteristics of the sound. For example, if a sustained A4 note produced by a violin is fragmented into a small segment, emphasizing only its temporal aspect may result in a

[5] For more details see Chapter 2; "2.2: Psychoacoustics, and Sound Perception in Sonification"

diminished ability to discern the pitch and a potential modification in the perceived tone quality, causing it to resemble a brief, abrupt "click."

Each of these aspects presents distinctive advantages in auditory perception, but the most remarkable aspect of human hearing may be its capacity to determine sound location. In contrast to vision, which is primarily focused forward, human hearing operates in a spherical manner, enabling varying degrees of precision in all directions. The pinnae, which filter sound from behind, above, and below, introduce a third dimension. As signals are transmitted from the ears to the brain, the brain learns and enhances its ability to discern the locations of sound sources. Personalized calibration accommodates the unique variations in the anatomy of the pinnae.

The exploration of sound spatialization seems to represent a pioneering step in unlocking the full range of sound characteristics. While past attention has been devoted to refining aspects like pitch, loudness, and timbre, the current century might mark a shift towards prioritizing the spatial dimension, wherein musical elements are anchored in the location of sound. This emerging direction is noticeable within the realm of sonification, where despite the availability of numerous algorithms for simulating sound movement, their application remains limited. Spatialization, often overlooked in both human auditory perception and sonification practices, presents abundant opportunities for advancing cognitive understanding.[6]

Expanding cognitive capacity through the integration of multiple senses is a recognized principle in cognitive load theory, experiencing renewed interest in the era of big data. The simultaneous utilization of two or more senses is likely to enhance the ability to process a greater amount of information, with each sense dedicated to a distinct data input. For instance, simultaneous visual and auditory perception of two data sources may augment cognitive capacity compared to solely relying on visual input.[7]

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[6] Paul, A. K., 2002.

[7] For this reason I value the integration of sonification and visualization techniques in my artworks as it expands cognitive capacity.

Although combining sonification with visual and other sensory inputs, particularly within the realm of virtual/augmented/mixed reality technologies, presents advantages, sonification remains a relatively new area of study. Despite extensive research over the years, there is still much to explore and define regarding its distinct capabilities, independent of other sensory inputs that might complicate evaluations. While the concept of using sonification to unveil entirely novel patterns within datasets can underscore its significance, it's important to acknowledge that sonification may also be perceived as an aspect of scientific multimedia that has not been fully exploited for its potential to evoke awe and engagement.[8]

1.2.4: Sonification Terminology

The precise beginnings of the term "sonification" are somewhat ambiguous. It could be argued that its earliest formal recognition in an academic setting dates back to 1990,[9] when it was characterized as an auditory complement to data visualization. Over time, the definition of sonification has evolved continuously, resulting in numerous related but distinct interpretations, many of which are currently in use simultaneously. Worrall, in his thorough examination of sonification,[10] offers perspective on the term's development and suggests a comprehensive definition:

> Data sonification is the acoustic representation of data for relational interpretation by listeners, for the purpose of increasing their knowledge of the source from which the data was acquired.

Kramer (1997)[11] offered a widely referenced definition of sonification that remains influential today:

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8 Ballora, M., 2014.

9 Rabenhorst, D. A., et al., 1990.

10 Worrall, D., 2009.

11 In 1999, Kramer provides a more streamlined definition, characterizing sonification as "the use of non-speech audio to convey information”.

> Sonification is defined as the use of nonspeech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation.[12]

This definition highlights several key features: Firstly, it delineates a process of conversion, whereby something initially inaudible is rendered into sound. Secondly, it underscores the relational aspect, focusing on conveying relationships rather than precise numerical data. Thirdly, it denotes the purpose of sonification as either communication or interpretation. The clearest exclusion is the categorical dismissal of speech displays, while the other aspects of the definition seem more flexible.

Contrast this with a more recent attempt to define sonification, as presented by Thomas Hermann in 2008.[13]According to Hermann, sonification refers to a method utilizing data as input and producing sound signals, meeting specific criteria. Hermann outlines criteria necessitating that the sound reflects objective relationships or properties within the input data, that the transformation is systematic, reproducible, and that the same procedure can be applied to different datasets. Unlike the previous definition, Hermann's criteria explicitly emphasize the systematic and reproducible nature of sonifications. It's not sufficient for the sound to convey information about the underlying data relationships; rather, these relationships must be systematically structured, and the resulting sound output must remain consistent across repetitions of the process.

This updated interpretation entails establishing a clearer and more rigid boundary between "scientific sonification" and "artistic sonification," effectively negating the existence of the latter category entirely and thus rendering the differentiation obsolete: "Being a scientific method, a prefix like in 'scientific sonification' is not necessary".[14] According to Andrew Abbott (1988), characterizing sonification in this manner also implies that it falls under the domain of scientists,

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[12] Kramer et al. 1997; original emphasis.

[13] Hermann, Thomas., *Taxonomy and Definitions for Sanification and Auditory Display*, 2008, pp. 2

[14] Hermann 2008, pp. 3

specifically those with a deep understanding of the established practices in sonification research. While involvement from artists and composers is not entirely excluded, they must adhere to a clearly defined scientific rationale at the very least.[15]

This point is noteworthy: While certain artists may not explicitly employ the term 'sonification,' there exists a substantial tradition, particularly evident in contemporary classical music and sound art, wherein data is converted into sound for musical objectives.[16] Conversely, some scientists utilize sound as a means of engaging in outreach activities. For instance, certain asteroseismologists incorporate "the sound of a star" into their public presentations to illustrate the concept of stellar oscillations, a focal point of their research. While these scientists may view such sounds as effective aids for outreach, they typically maintain a degree of skepticism regarding the scientific precision and dependability of sonification techniques. Consequently, they may not prioritize delving into the intricacies of the sound generation process.[17]

The crucial issue was not the specific standards Hermann proposed, but rather the broader question of whether it's advisable to restrict the boundaries of the field. It could be argued that any definition ought to be adaptable enough to accommodate future developments within the sonification community, rather than endorsing any one particular understanding of the community and its methods. Barrass[18] contends that "the idea of making sonification more scientifically rigorous is misguided," as it may suit certain approaches within the field but not necessarily other traditions influenced by different theories, such as humanist perspectives. If an artist were to create a compelling sonification that effectively communicates something about a dataset without meeting all of Hermann's criteria, it would be detrimental to the field if such an example couldn't be recognized as sonification.

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[15] Abbott, A., 1988.

[16] Schoon, Andi, and Florian Dombois, 2009.

[17] See Alexandra Supper's interviews with Conny Aerts, John Heise & Donald Kurtz, 2014.

[18] Stephen Barrass, 2008.

Bukvic (2020) offers a concise and inclusive description of sonification as "audio that conveys information,"[19] which encompasses a wide range of applications, including human speech, music, and environmental sounds. This definition expands the conventional understanding of sonification, which usually involves purposeful manipulation of sound by humans for human consumption, thereby creating novel avenues for studying and understanding our interactions with the environment. These observations could potentially stimulate novel strategies for developing deliberate data sonification techniques.

1.2.5: Sonification and Boundaries of “science" and “art”

Defining the scope of sonification often raises questions regarding the interplay between science and art, a topic I delve into further in this section. Previous discussions have highlighted efforts to delineate sonification as a scientific endeavor, emphasizing objectivity and reproducibility, in contrast to musical approaches aimed at sonifying data. This distinction has sparked debates, seemingly pitting one faction advocating for strictly "scientific" sonifications and distancing from artistic influences against another faction that emphasizes the value of artistic input and advocates for inclusivity. However, such a binary interpretation oversimplifies the complexity of the issue. For instance, it is challenging to reconcile this dichotomy with the performance by Thomas Hermann, ostensibly aligned with the "scientific faction," at the 2008 Wien Modern festival for contemporary music. Hermann, alongside Gerold Baier, presented a "live sonification of the human EEG," utilizing composer Alvin Lucier's brainwaves,[20] which challenges the notion of strict boundaries between scientific and artistic approaches to sonification.

Rather than a static issue of entrenched factions within the sonification community vying to assert their interests and impose their particular vision of scientific/artistic sonification,

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[19] Bukvic, I., 2020.

[20] Alvin Lucier's 1965 work "Music for Solo Performer" provides an early example, wherein Lucier sat on stage with electrodes attached to his head. These electrodes were connected to an alpha amplifier, which in turn was linked to a set of loudspeakers. Positioned in front of these speakers were percussion instruments, which were 'played' by the pressure of the sound waves emanating from them. Unlike typical electronic music, the loudspeakers in Lucier's composition acted not as direct sound producers but rather as transducers or triggers for the natural resonant sounds of the percussion instruments. (Mumma 2011: 80)

Alexandra Supper[21] illustrates that these boundaries are subject to negotiation in specific contexts. For instance, consider a presentation on sonification at a neurological workshop recounted by Gerold Baier: When Baier and his colleague showcased their EEG sonification, a prominent figure in neurology ostentatiously left the lecture hall, prompting several other researchers to follow suit. Even those who remained exhibited reactions akin to those seen at avant-garde jazz performances in their heyday: mouths agape, expressions of disapproval, and bewilderment at the unfamiliarity of the presentation. Those who engaged with the presentation insisted on interpreting it through a musical lens rather than a scientific one, much to the chagrin of the presenters, who intended to discuss their findings regarding epileptic data rather than matters of composition. Nonetheless, despite the presenters' objections, the association of their presentation with music was not entirely incidental, as evidenced by the title of their talk (referencing an "unpredictable concert"), which naturally evoked musical associations.

This case study is intriguing because it integrates two aspects of boundary work typically addressed separately: Boundary work scholars often concentrate solely on the rhetorical delineation of a field,[22] or they analyze interdisciplinarity in terms of boundary crossing. However, in this instance, we observe a simultaneous occurrence of both; Demarcation and boundary crossing transpire concurrently. As noted by Willem Halffman, "boundary work has the double nature of dividing and coordinating,"[23] of delineating while also specifying conditions under which boundaries can be traversed. In the aforementioned anecdote, the prospect of transcending the boundaries between science and music was what initially facilitated participation in this scientific forum. Nonetheless, the presenters themselves were reluctant to be associated with music, promptly distancing themselves rhetorically from being identified with the artistic aspect of the science-art continuum. This illustrates that the positioning of sonification in relation to science and/or art is not predetermined but rather a delicate balance influenced by strategic decisions and the pursuit of an audience, as well as the preferences of

[21] Supper, 2014.

[22] Gieryn, Thomas F, 1995.

[23] Halffman 2003, pp. 70

practitioners. In essence, the categories of "science" and "art" do not denote rigidly delineated domains; the boundary between them is permeable and adaptable, subject to boundary work.

Nonetheless, the act of boundary crossing is intertwined with delineation, and those engaged in sonification often emphasize the importance of delineating between sonification and music. For instance, during a presentation at a contemporary music festival, a sonification researcher humorously greeted the audience by stating: "I am glad to see that you dared to approach this topic even though it has nothing to do with music." Although the remark elicited laughter, it conveyed a clear message: Sonification should not be conflated with music. Similarly, interviews with Supper reveal a rhetoric of demarcation.[24] One interviewee stressed that sonification, like visualization, allows for some artistic expression but remains fundamentally a technical process with rules. They emphasized that just as a visualization differs from a painting, sonification cannot be automatically equated with musical composition.[25]

Individual practitioners must confront the issue of determining their own boundaries. When queried about the possibility of transforming his dissertation into an art project, media artist and researcher Florian Grond responded that he might entertain the idea but would proceed with great caution:

> If you approach chemists about sonification of chemistry, at first they always believe that it's art anyway. And then it's counterproductive, of course, if you end up using it as art because then it's just difficult to communicate why one thing was not art and the other thing suddenly is art.[26]

Grond worries about muddling the message for the chemists he wants to collaborate with; sonification as art “has a very, very decorative function that is mostly on the level of infotainment and actually of a justification for all the money being spent on these [large-scale research] projects. It's about public relations and all that.”[27] The demarcation here is not an

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[24] See Supper’s interviews, 2014.

[25] See Supper’s interview with Florian Dombois, 2014, pp. 3

[26] See Supper’s interviews with Grond, Florian Grond, 2014, pp. 4

[27] Ibid, pp. 6

essentialist distinction between science and art but a pragmatic realization that "by and by, you learn to detect what 'art' means for the art system and what 'science' means for the science system".[28]

The criticism directed towards the use of sonification in art prompts a response in the form of this thesis: While sonification art may not suffice for scientific inquiry, it does not imply that it lacks value or is inferior to scientific sonification. Sonification art offers an interpretation of data, thus contributing to its significance. This response is elaborated upon in subsequent sections, particularly in the segment highlighting the role of the artist as a researcher. Additionally, I demonstrate through my compositions portfolio accompanying this thesis, that the integration of sonification techniques with musical composition methods yields "music".

1.2.6: The Artist as Researcher; A Case Study

In August 2007, Johnjoe McFadden, a professor specializing in molecular genetics at the University of Surrey and renowned author of "Quantum Evolution," authored an article in The Guardian, marking the commencement of a distinctive investigative journey:

> In his famous two cultures[29] lecture, CP Snow lamented the deep divide that separates the arts and humanities in modern culture. But recent work published in Genome Biology by researchers Rie Takahashi and Jeffrey H Miller at the University of California, Los Angeles (UCLA), might be a step towards healing the rift. the scientists designed a computer programme [sic] that turns genes into music. The resulting tunes are surprisingly melodic and have a curious resonance with the roots of both Western music and science 26 centuries ago.[30]

McFadden outlined a plan in which 20 amino acids were originally matched with notes on the twelve-note chromatic scale. However, the resulting compositions lacked melody. To rectify this,

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[28] Ibid, pp. 2

[29] The Two Cultures is a reference to the existence of two separate cultures with little contact between them — one is based on the humanities and the other on the sciences [Vickers, 1999, p. 2] a divide which James [Jamie James, 1993, pp. xiv] described as a "psychotic bifurcation". James summarized the situation thus: "In the modern age it is a basic assumption that music appeals directly to the soul and bypasses the brain altogether, while science operates in just the reverse fashion, confining itself to the realm of pure ratiocination and having no contact at all with the soul. Another way of stating this duality is to marshal on the side of music Oscar Wilde's dictum that 'All art is quite useless,' while postulating that science is the apotheosis of earthly usefulness, having no connection with anything that is not tangibly of this world. [p. xiii]

[30] McFadden, J., 2007.

Takahashi and Miller grouped similar amino acids together, assigning them to a single note within the seven-note diatonic scale. This enabled amino acids to represent three-note chords. The rhythm was determined by the frequency of the DNA code for each amino acid, while melodies were derived from proteins such as *thymidylate synthase* A and segments associated with Huntington's chorea, resulting in unique musical pieces.

McFadden's article highlights a reversal of Snow's argument concerning the relationship between art and science, emphasizing the limited awareness among scientists regarding cultural advancements, particularly within the realm of art.

> It's nearly 50 years since CP Snow delivered his famous lecture, but the arts and sciences are as far apart as ever. Takahashi and Miller's transposition of science into music repays an ancient debt; but perhaps also reminds us that the complementary disciplines have a common root, and once shared the same interests.[31]

McFadden highlighted a shift in perspective from Snow's ideas regarding the interplay between art and science. Instead of suggesting a lack of scientific knowledge among individuals in the arts and humanities, it brought to light the deficiency of many scientists in understanding cultural advancements, particularly in the realm of art. The article illuminated a significant disparity in comprehending historical progressions in art concerning science. As articulated by Charlie Gere in "Art Practice in A Digital Culture," McFadden's assertion that a program converting gene sequences into music bridges the gap between art and science overlooks decades of collaborative efforts among artists, scientists, and engineers, yielding work of substantially greater artistic and scientific significance. This extensive heritage encompasses early ventures in computer graphics and animation by scientists at institutions like Bell Labs during the 1960s, as well as collaborations between artists, scientists, and engineers within groups like Experiments in Art and Technology and the Computer Arts Society (E.A.T)[32] during the same era.

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[31] McFadden, J., 2007.

[32] Refer to https://www.experimentsinartandtechnology.org/

It also encompasses explorations into complexity during the 1970s and 1980s by artists from establishments such as the Slade alongside scientists in places like Santa Fe. Additionally, it includes the longstanding tradition of artistic inquiries into robotics and artificial intelligence, from pioneers like Edward Ihnatowicz to contemporary figures like Simon Penny, as well as collaborative endeavors with scientists on genetics and neuroscience by artists such as Oron Catts, Annie Cattrell, Ruth Mclennan, and Jane Prophet. Notably, the recent endeavors of the Critical Art Ensemble examining the cultural implications and consequences of biotechnological research deserve special mention, particularly in light of CAE member Steve Kurtz's recent apprehension under the Patriot Act in the United States. The revival of CP Snow's two-cultures argument is portrayed as if it holds profound truths about our culture, rather than being an outdated polemic. If there exists a division, it lies not within contemporary culture at large, but rather in how institutions like Tate Modern London and the Science Museum uphold and reinforce unwarranted rigid distinctions between the arts and sciences.[33]

The concept of experimentation permeates our culture, influencing our lives as an ongoing process of trial and error. Culture serves as the arena where experiments take place, a phenomenon originating from the Renaissance, the advent of modern scientific thinking, Romantic ideals of self-expression, and the dominance of market capitalism. Max Weber suggested in 'Science as Vocation' that the experimentation of Renaissance artists such as Leonardo da Vinci facilitated the development of the scientific method. Capitalism, especially in its later stages, capitalizes on exploiting individuals' experimental tendencies and the desires these tendencies uncover. Figures like Charles Darwin, Karl Marx, and Friedrich Nietzsche also contributed to the culture of experimentation during the nineteenth century.

In the twentieth century, Sigmund Freud emphasized the continuous experimentation in reality assessment that influences our comprehension. The most evident product of this experimental ethos is science, which has not only profoundly altered our way of life but also reframed our perspectives on the world. Nonetheless, science represents merely one aspect of this wider experimental milieu.

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[33] Gere, C. 2010.

At the same time, art showcased a spirit of experimentation through avant-garde movements, where experimentation emerged as a vital tactic and form of artistic expression. This trend spanned from the initial explorations of DADA, the Futurists, and the Surrealists to subsequent avant-garde movements after the war, encompassing figures such as John Cage, and movements like Fluxus, early performance, video and conceptual art, experimental music, free jazz, and improvisation.

During the mid-twentieth century, artists began to view themselves as experimental investigators, as demonstrated by the establishment of organizations such as Experiments in Art and Technology in 1966, and the emergence of 'Arts Labs' in Britain in the late 1960s. The idea of the “artist as researcher,” and even the “artist as ethnographer,” as described by Hal Foster in the 1970s and 1980s, further underscored this experimental function.

The definition of an "artist-researcher" provided by the Social Sciences and Humanities Research Council of Canada pertains to individuals affiliated with Canadian post-secondary institutions whose endeavors encompass both research and artistic creation. According to their framework, Research-Creation encompasses any research endeavor inherent to a creative process or artistic domain that significantly contributes to the generation of literary or artistic works. Applicants are expected to articulate precise research inquiries, provide theoretical contextualization, and outline a methodological approach that aligns with recognized standards of excellence, with resulting outputs suitable for publication, public presentation, or exhibition.[34]

1.3: Artistic Context

1.3.1: Artistic Practices, Creativity, and Integration of Technology

[34] Jefferies, J. K., 2010, p.32.

Artists possess a natural curiosity about their creative process. They regularly engage in introspection regarding the potential results of unfamiliar forms of expression and continually uncover connections between their concepts and chosen modes of artistic representation. At times, it can be challenging to discern whether the artist's concept dictated the choice of a specific medium or if the process of familiarization with the medium led to the emergence of novel artistic expressions.

Maybe delving too deeply into the analytical aspects of creative processes, which are often intricately connected and reliant on each other, could pose a risk. The crucial aspect to grasp is that artists must reach a stage where their creations take a shape that satisfactorily addresses these discussions and aligns with their individual creative vision. This enables them to progress and create additional works that expand upon their insights and cultivate their artistic practice in a consistent direction or opt for a complete change of course.

Artists are intrigued by technological advancements that unexpectedly grant them entry into entirely new realms of creativity. While they must learn the guidelines and procedural techniques necessary to explore these territories, they embrace this process of becoming acquainted and the corresponding dedication it often demands. The feeling that they are venturing beyond boundaries previously unexplored in the same manner ignites a sense of pioneering endeavor.

1.3.2: The Intersection of Art, Science, and Technology

Occasionally, comprehending the precise equilibrium necessary for an artist to finalize work incorporating both technologies and specialized subject knowledge can be challenging. Their concepts evolve through a discourse between artistic intent and the technical implementation upon which it relies.

The consequences, regarding both time allocation and resource utilization, of engaging in interdisciplinary work between art and technology are substantial. Frequently, artists keenly acknowledge that their struggle to comprehend new concepts and their specialized training might render certain types of knowledge exceptionally challenging for them. Moreover, there is a perception that these limitations may be glaringly evident to the established communities of scientists and technologists serving as intermediaries between the artist and the methodologies they seek to employ, resulting in inherent tensions.

Artists may sometimes be perceived as slow-paced and self-focused in their methods, contrasting with the inherent dynamism found in conventional scientific research practices. Conversely, scientists may appear uncooperative to individuals seeking their aid, occasionally hesitant to share their expertise with those whose objectives might not be immediately apparent to them. These instances typically stem from different communication modes rather than deliberate efforts to impede progress.

Scientific research proceeds from one measurable outcome to another, and moves logically towards its objective. For example, a solution to the problem, the isolation of a particular element, or the presentation of quantifiable evidence that opens the way to the commercial manufacture of a substance. Artists also work with similar outcomes at times, but their impetus lies in a desire to find some kind of mediation for a particular experience, and in many cases they work with no definite objective in view as they tend to feel their way tentatively, rather than following a carefully charted route.

1.3.3: Data to Art; Data as a Creative Asset

Data is coming into its own as a vital resource in the production of significant artworks. Artists have a role to play in influencing the way in which others approach the data that has been made available. They can open up all sorts of possibilities for new kinds of collaboration between science, and artistic intentionality. Artists can also show how data can become the mean for expression by which communities are drawn into discussion about key social issues, for instance.

Data may be just numbers, but they can represent critical contemporary statistics that have consequences for people around the world. It is important that we accept responsibility for data that is available and that it is not seen as something neutral and without real significance or meaning. All knowledge carries with it implications for action, and any data that is used must necessarily entail some sort of reaction at the point where it is collected and evaluated.

Artists engage with data for various reasons; firstly, some artists are motivated by a desire to address the pervasive unease surrounding the influence of data in society. Secondly, artists are drawn to found materials, often overlooked by others. In an information-centric society, data is abundant and serves as a "found material" for artists, offering hidden natural patterns and trends that intrigue contemporary artists. Thirdly, data is dynamic, continuously updated moment by moment. Live digital art relies on this continual refreshment of data sources.[35]

1.3.4: Imagination Meets Data

Artists often thrive on engaging with elements that others might overlook, resulting in many instances of creative work stemming from their manipulation of statistical and various other data forms. The key challenge is to create an interface for such data that is suitable and effectively supports the artist's vision. This interface should also enable viewers to perceive the data in a new context and ensure it is accessible. While the precision of the data remains intact, the artist reimagines and restructures it within a novel framework.

Imagination and data might initially appear to be an unlikely pair. Data often gains prominence in practical contexts where task completion is essential. Its frameworks are rooted in a materialistic perspective where everything can be measured and somewhat predicted. Conversely, imagination is crucial at the inception of any idea and is linked with innovation and advancement. When imagination is involved, the unexpected should be anticipated.

[35] Colson, Richard, 2007.

1.4: Research Objectives

This research-creation project serves a dual purpose: firstly, to enrich the dynamic landscape of digital humanities and advance our comprehension of how technology can catalyze innovative modes of scholarship, collaboration, and knowledge dissemination within the humanities. Secondly, it aims to showcase the transformative potential of aural representations in data analysis. By employing sound as a medium for portraying complex datasets, the project endeavors to deepen our perception of the world and to expand the boundaries of creative expression. Through sonification techniques, it seeks to unveil hidden patterns and insights within the data, inviting audiences to engage with information in novel and immersive ways. Ultimately, by integrating elements of art, technology, and scholarship, this initiative aims to inspire interdisciplinary dialogue and to foster fresh avenues for exploring the intersections between data, culture, and creativity.

Consequently, this inquiry aims to comprehend the applications of sonification at the convergence of science and art, emphasizing the collaborative potential of sonification with visual data representations. Moreover, the project endeavors to create auditory and visual encounters by sonifying extensive datasets, and to transform these sonified data into engaging audiovisual artworks, integrating techniques of sound-based composition and synchronized data visualization. This process will serve as the portfolio component of the research-creation thesis.

1.4.1: Research Aims

The primarily aims of this research-creation thesis are:

1. To define the theory of sonification, including its classification and methodological approaches.
2. to present an aesthetic framework for sonification art, focusing on aesthetic perception and the associated design complexities. It will provide an overview of current

sonification practices, with a specific emphasis on their application within artistic contexts, showcasing the manifold possibilities that sonification can offer in the realms of art and humanities.

3. To establish a framework for sonification as a tool for composition, defining "sonification art".
4. To create a collection of sonification artworks encompassing diverse datasets sourced from various scientific domains or personal data, including data generated for specific purposes or through designed algorithmic systems. The creation of the sonification pieces will involve employing a mix of datasets, musical styles, performance contexts, and multimedia strategies.
5. To underscore the credibility of practice-based research (research-creation) as a viable approach in sonification research and academia at large, with a focus on advancing scholarly endeavors.

1.4.2: Research Questions

A few inquiries pursued by this study include:

1. What sets apart an artistic sonification from its scientific counterpart, and what are its unique applications and features?
2. What types of data and sound characteristics are applicable in the creation of sonification art?
3. Familiar musical elements like pitch, rhythm, and harmony can significantly augment data comprehension when employed in parameter mapping. The optimal mapping of data to sound properties, however, involves considering various factors, such as identifying the task-related aspects suitable for sonification and determining the extent of data suitable for auditory display. One pertinent question raised is: how much of this data is useful for auditory presentation?

4. What auditory dimension and parameter should be employed, and how to map the data to the chosen parameter?
5. What constitutes the aesthetics of sonification? How do they manifest audibly? Are there particular principles that, if formulated, can ensure (or at least increase the likelihood of) successful aesthetic representation?
6. What are the criteria that can determine the functional and aesthetics qualities of a signification art?

1.5: Methodology

A growing body of research into sonification, whether originating from intentional scientific investigation or stemming from artistic installations, sound art, or compositions, has generated a variety of approaches for converting data into auditory representations. The primary methodological considerations employed in this thesis are outlined as follows:

1.5.1: Parameter Mapping[36]

The primary methodology utilized in this research-creation thesis involves the utilization of the "parameter mapping" technique. Parameter mapping stands as the predominant method for translating data into sound. Typically, a data dimension is translated into an auditory parameter, such as duration, pitch, loudness, position, brightness, clusters, movements, among others. Various variables can be assigned to different parameters simultaneously, resulting in the creation of intricate soundscapes. The parameter-mapping technique offers several advantages:

- Simplified production: Existing tools facilitate the mapping of data to numerous auditory parameters.
- Multivariate representation: Multiple data dimensions can be audibly represented simultaneously.

[36] Refer to chapter 3, specifically section 3.2 titled "Parameter-Mapping," for an in-depth exploration of this topic.

1.5.2: Algorithm Development

A crucial aspect of this research involves developing algorithms for parameter mapping through coding. This process ensures precise mapping of data parameters to sound characteristics, facilitating a seamless and dynamic transformation of data into sound.

1.5.2.1: The medium of code

Engaging with programming often entails feelings of frustration, bewilderment, and awe at the considerable time investment needed to accomplish relatively minor tasks. However, with appropriate guidance and perseverance, a subsequent phase emerges where confidence and a feeling of accomplishment propel individuals to pursue further advancement and exploration. To delve deeper into the realm of programming, artists must transition to a stage where they start to recognize the sophistication of coding structures, the exactness demanded in formulating statements, and the versatility afforded for posing challenges and devising resolutions.

Currently, programming serves as a tool for artists, moving beyond limiting idea formation to leveraging the computational capabilities of computers to fulfill their objectives. Similar to other artistic media, the chosen medium not only influences the creative process but also shapes the ultimate expression of the work. Code as medium offers artists a unique range of auditory and textural elements, expanding their array of creative possibilities in particular directions.

One might argue that presently, code possesses a quasi-empathetic quality. It sheds its former reputation of being cumbersome, complex, and enigmatic, instead offering intuitive responses and suggestions in a collaborative relationship with the artist. Artists utilizing computer programs in their creative process also generate preliminary designs and drafts. Their toolkit comprises loops, conditional statements, real numbers, integers and abstractions, while their drafts may manifest as program outputs. Thus, programmers formulate specifications for "the individuals of little societies”[37] rather than simply crafting sequences of instructions. Despite their efforts, they may struggle to foresee all the intricacies of these interactions beforehand, which underscores the necessity of utilizing computers in the process.

1.5.2.2: Why code?

Code serves specific purposes, with software developers striving to create user-friendly products where the code remains discreet, functioning invisibly behind the interface's simplicity. Writing code reveals that every visible element on a computer screen is generated by a statement in a program. Attributes such as screen color, font size, or cursor shape are manipulable through code, granting control over the computer's operations. However, many commercial software products limit this access, prioritizing the needs of the largest user base, typically commercial clients, over creative possibilities. Consequently, artists who eschew commercial software may explore working directly with computer components as a routine aspect of their practice, transitioning from commercial software to coding for greater flexibility and customization.

1.5.3: Practice-as-Research

In this section, I focus on the “practice-as-research" methodology, a framework closely aligned with the concept of “research-creation” frequently employed within Canadian academic setting. This method integrates artistic practice with scholarly investigation, facilitating the exploration of intricate research inquiries through creative means. The subsequent discourse delineates the fundamental principles and procedures intrinsic to practice-based research, underscored by its pertinence to the present investigation.

The experimental phase of this dissertation employs a practice-as-research methodology to address certain research queries. Nelson[38] characterizes it as a 'mixed-mode research' technique

[37] Colson, 2007, pp. 95

[38] Nelson, 2006, pp. 114

that amalgamates "practitioner knowledge," "critical reflection," and a "conceptual framework." These three modalities mutually inform each other to engender knowledge (refer to Figure 1); my experiential knowledge and competencies are applied and critically evaluated within musical and sonification contexts.

The concept of practice-as-research is still in its nascent stage, yet it shares numerous similarities with conventional research methodologies. According to Leavy, there are parallels between them:

> […] art and science bear intrinsic similarities in their attempts to illuminate aspects of the human condition. Grounded in exploration, and representation, art and science work toward advancing human understanding. Although an artificial divide has historically separated our thinking about art and scientific inquiry, a serious investigation regarding the profound relationship between the arts and sciences is underway.[39]

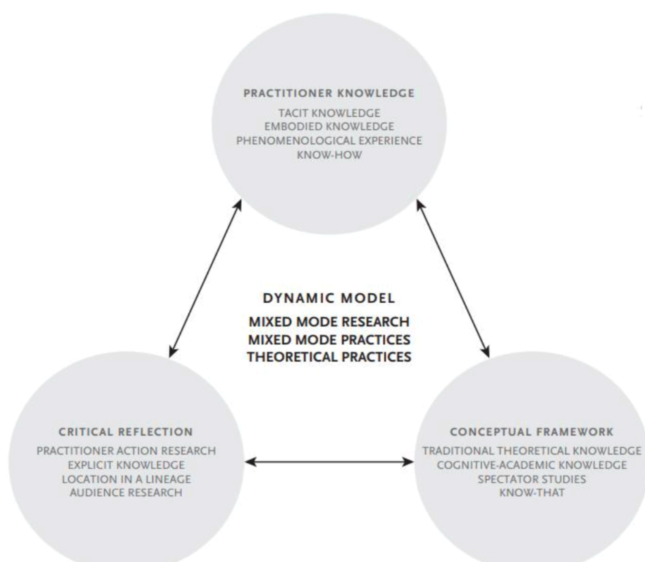

Figure 1: *For mixed-methods research, illustrating the interconnectedness of 'practitioner expertise,' 'critical introspection,' and a 'theoretical framework' within practice-based inquiry.*

[39] Leavy, 2015, pp. 3-4

Examining the definition provided by the Organisation for Economic Cooperation and Development (OECD) defining practice-based research: “Creative work undertaken on a systematic basis in order to increase the stock of knowledge of humanity, culture and society, and the use of this stock of knowledge to devise new applications”.[40] The scientific approach involves initial observation, followed by analytical reflection on the observed phenomena to identify patterns and discrepancies, and then conducting further observations, often in controlled settings conducive to planned experimentation.[41]

For a composer, research can be remarkably similar. Departing from a hypothesis (sonification can be a compositional tool) research questions are formulated (for example, which are the best data to sound mappings for a musical piece?); an evaluation of this practical work will lead the necessary knowledge to implement sonification as a compositional tool (or decide against it!).

The outcomes of practice-as-research may not necessarily manifest as “text-based, but rather a performance (music, dance, drama), design, film, or exhibition.” This is because, despite being a research methodology, it places substantial emphasis on creative practice, often resulting in performance-based outputs.[42] In the context of this project, the culmination consists of a thesis and portfolio delineating and implementing innovative frameworks for composition and sonification within artistic contexts.

1.6: Thesis Structure

This thesis is structured into four main chapters, each dedicated to exploring distinct aspects of sonification and its application within auditory displays, sound studies, and artistic expression. The organization aims to provide a comprehensive examination of theoretical foundations,

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[40] OECD, 2002, p. 30

[41] Weatherall, 1968, p. 3

[42] Arts and Humanities Research Board, 2003, p. 10

practical techniques, and artistic contexts related to sonification, such as how sonification fits within the broader artistic context, potentially including its aesthetic considerations, creative processes, and implications for artistic expression.

Chapter 1 introduces the thesis "How Data Sound," exploring sonification within Digital Humanities, emphasizing its potential for enriching data exploration through auditory means. The literature review examines foundational concepts like data, information, and knowledge, and discusses auditory perception and sound characteristics. It contextualizes sonification within artistic practices, integrating technology and fostering creative processes. Moreover, research objectives and methodology are outlined, detailing aims, questions, and approaches used in this study.

Chapter 2 establishes the theoretical groundwork by delving into key concepts such as the classification of sonification, limiting factors, and the role of psychoacoustics and sound perception in sonification design. It also examines the principles of auditory-visual interaction and explores various dimensions of data representation through sound.

Chapter 3 focuses on practical techniques and methodologies for sonification, including audification, parameter mapping sonification (PMSon), model-based sonification (MBS), and other approaches. Each technique is analyzed in detail, highlighting its applications, case studies, and implications for artistic expression.

Chapter 4 shifts the focus to the artistic dimensions of sonification, exploring its design principles, and aesthetic considerations. This chapter also lays down a framework for sonification as art, and presents a definition of sonification in the artistic context. Moreover, the chapter discusses a portfolio of my compositions, demonstrating the creative potential of sonification in generating immersive audiovisual experiences.

1.7: Conclusion

This thesis in research-creation stems from my profound fascination with the intersection of art and technology, particularly focusing on the conversion of data into audiovisual presentations. As a contemporary composer and sound artist, I explore how creatively interpreting data can enhance the public's understanding of the subject matter. The increasing interest in data-driven art across various artistic domains significantly influences my motivation and guides my methodological framework. This dual inquiry unfolds within the realms of digital humanities and sound studies, encompassing the examination of existing data sonification endeavors and the development of immersive experiences using extensive datasets. The selected methodology emphasizes the "parameter mapping" sonification approach, seamlessly merging with data visualization to establish a comprehensive and multi-sensory expression of datasets.

The primary objective of this thesis is to contribute to the digital humanities landscape, emphasizing the transformative potential of aural representations in both data analysis and artistic meaning-making. By bridging the gap between science and art, this thesis aims to push the boundaries of creative expression. Recognizing the early stage of the field of sonification and the diverse possibilities for sonifying datasets, the thesis acknowledges the case-specific nature of the outcomes, underlining the artistic authenticity, originality, and individuality inherent in the synthesis of art and technology.

Chapter 2 - Fundamentals of Sonification

2.1: Sonification Theory

An *auditory display* encompasses any presentation employing sound to convey information. Specifically, sonification is characterized as a subset of auditory displays utilizing non-speech audio to depict data. Kramer et al. expanded upon this definition by elaborating that:"sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation."[43]

A more contemporary interpretation of sonification has been suggested, aiming to broaden and refine its definition by specifying it as "[…] the data-dependent generation of sound, if the transformation is systematic, objective and reproducible." Sonification seeks to convert data or information into sounds, leveraging human auditory perception to enhance the comprehensibility of these relationships[44].

Theories provide empirically-supported explanations of the connections among variables. According to Hooker, theories strive to render the world understandable by not only describing how things are but also why they are that way: "Theory represents our best efforts to make the world intelligible. It must not only tell us how things are, but why things are as they are."[45] Sonification encompasses aspects of both science, which relies on theoretical frameworks, and design, which may not always be guided by scientific principles or theory.

The theoretical foundations applicable to and propelling sonification draw from a broad spectrum of disciplines including audio engineering, audiology, computer science, informatics, linguistics, mathematics, music, psychology, and telecommunications, among others. These fields

[43] Kramer et al., 1999.

[44] Hermann, 2008 & 2011.

[45] Hooker, 2004, pp.74.

collectively contribute to the conceptual framework of sonification, yet lack a singular comprehensive set of principles or regulations.[46] Instead, the principles guiding sonification in both research and practical applications stem from a synthesis of valuable insights derived from the intersection of these diverse disciplines. While numerous generalized contributions have been made towards the theoretical underpinning of sonification, a complete and cohesive theoretical framework to steer research and design endeavors has yet to be articulated by scholars and practitioners. Recent years have witnessed a resurgence of interest and robust discourse surrounding this subject matter.[47]

The collaborative Sonification Report of 1999[48] served as an initial framework for meaningful discourse on sonification theory by highlighting four key areas meriting attention in theoretical discussions on sonification. These encompassed:

1. Categorizations of sonification techniques grounded in psychological principles or display applications;
2. Examinations of the types of data and user tasks suitable for sonification;
3. Considerations regarding the mapping of data into auditory signals; and
4. Deliberations on the factors constraining the adoption of sonification.

By addressing the contemporary status of these four domains, this chapter aims to provide a comprehensive introduction to sonification, alongside elucidating the guiding theoretical underpinnings for this thesis. It endeavors to draw upon insights from pertinent research domains, providing insightful clarifications to illuminate the present state of the field.

2.1.1: Sonification within Auditory Displays

[46] Edworthy, 1998.

[47] As an example: Brazil & Fernstrom (2009), de Campo (2007), Frauenberger, Stockman, & Bourguet (2007b), and Nees & Walker (2007) have been cited.

[48] Kramer et al., 1999.

Sonification represents a relatively new category of auditory displays. Similar to any information system (refer to Figure 2), an auditory display functions as an intermediary between the information source and the recipient. Specifically, in an auditory display, the relevant data are transmitted to the human listener via sound.

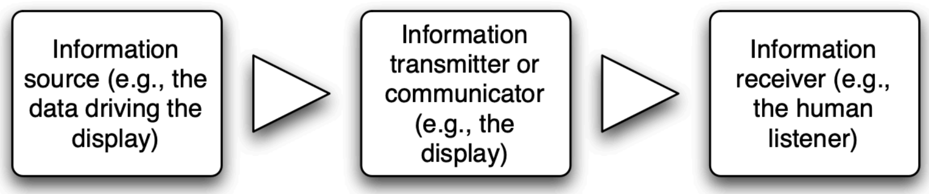

Figure 2: *General description of a communication system.*

Despite research into audio as a means of information display dating back over half a century,[49] it is only with the advent of digital computing technology that auditory displays have become widespread. Edworthy (1998) suggested that the development of auditory displays and audio interfaces was inevitable due to the low cost and ease with which electronic devices can now generate sound. Our environment is filled with devices ranging from cars and computers to cell phones and microwaves, all of which now utilize 'intentional sound' to convey messages to users.[50]

The reasons and motivations for presenting information through sound, instead of visually or through other means, have been widely explored in academic literature.[51] In summary, auditory displays leverage the human auditory system's exceptional capacity to detect temporal changes

[49] See Frysinger, 2005.

[50] Intentional sounds are purposely engineered to perform as an information display (see Walker & Kramer, 1996), and stand in contrast to incidental sounds, which are non-engineered sounds that occur as a consequence of the normal operation of a system (e.g., a car engine running). Incidental sounds may be quite informative (e.g., the sound of wind rushing past can indicate a car's speed), though this characteristic of incidental sounds is serendipitous rather than designed.

[51] Examples include: Buxton et al., 1985; Hereford & Winn, 1994; Kramer, 1994; Nees & Walker, 2009; Peres et al., 2008; Sanderson, 2006.

and patterns.[52] Consequently, auditory displays might be the optimal modality when the information involves intricate patterns, temporal variations, includes alerts, or necessitates prompt responses.

2.1.2: Classification of Auditory Display & Sonification

A classification system for auditory displays, and specifically for sonification, can be developed in various ways. Classifications often arise based on either the display's purpose or the sonification technique, with both serving as viable bases for categorization. In this chapter, I will discuss methods of classifying auditory displays and sonifications according to both their function and technique, highlighting how these aspects are deeply interconnected.

Sonification is undoubtedly a branch of auditory display, though the precise delineation of its boundaries remains uncertain. Hermann (2008) recently highlighted that for a sound to be classified as "sonification," it must meet criteria such as data-dependency, objectivity, systematicness, and reproducibility. Nevertheless, definitions within the sonification domain are often broadly outlined and somewhat adaptable.[53] Moreover, recent research on auditory displays incorporating speech-like sounds has challenged the notion of excluding speech sounds from sonification taxonomies.[54]

Although categorizing auditory displays can be challenging, such catalogs of auditory interfaces are valuable because they standardize terminology and inform readers about the available options for incorporating sound into interfaces. This chapter aims to offer a fundamental overview by

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[52] See Bregman, 1990; Flowers, Buhman, & Turnage, 1997; Flowers & Hauer, 1995; Garner & Gottwald, 1968; Kramer et al., 1999; McAdams & Bigand, 1993; Moore, 1997.

[53]For instance, auditory versions of box-and-whisker plots, diagrammatic data, and equal-interval time series have all been labeled as sonification, specifically "auditory graphs." However, these auditory displays are distinct from each other in both their structure and their purpose. (Herman, 2008)

[54] Jeon & Walker, 2011; Walker, Nance, & Lindsay, 2006b. Also see Worrall, 2009a for a discussion on this topic.

describing and defining, where necessary, the various types of sounds commonly employed in auditory interfaces.[55]

Ultimately, the label given to a sonification is far less significant than its effectiveness in conveying the intended information. Therefore, the classification provided here aims to align with standard naming conventions found in academic literature and the auditory display community. However, it is important to note that these classifications should not be interpreted as implying that clear and distinct boundaries can always be established or universally agreed upon, nor are such boundaries essential for creating a successful sonification.

2.1.2.1: Functions of Sonification

Considering that sound possesses inherent characteristics that make it advantageous for conveying information, we can start by examining several functions that auditory displays can serve. According to Buxton (1989) and others[56] these functions can be categorized into three main groups:

1. alarms, alerts, and warnings;
2. status, process, and monitoring messages; and
3. data exploration; and

   Bruce N. Walker and Michael A. Nees further expand these categories to include:

4. art, entertainment, sports, and exercise.[57]

The subsequent sections will provide a concise elaboration on each of the aforementioned categories.

[55] There are additional classifications and descriptions of auditory displays available in various sources (Buxton, 1989; de Campo, 2007; Hermann, 2008; Kramer, 1994; Nees & Walker, 2009), and an extensive collection of definitions for auditory displays has been documented (Letowski et al., 2001).

[56] See Edworthy, 1998; Kramer, 1994; Walker & Kramer, 2004.

[57] Nees, M. A., & Walker, B. N. (2009)

1. Functions indicating alerts

"Alerts and notifications" are auditory cues designed to signal the occurrence or imminent happening of an event or to prompt immediate attention to something in the surroundings. Typically, these alerts are straightforward and conspicuous, conveying minimal information. For instance, a beep commonly signifies the end of the cooking cycle in a microwave oven. Such alerts typically provide limited details about the event itself; the microwave beep, for instance, only indicates that the set time has elapsed, without necessarily implying that the food is fully cooked.[58]

"Alarms and warnings" are auditory cues designed to indicate the onset of a specific set of events, typically negative, demanding urgent attention or action.[59] Unlike simple alerts, alarms and warnings convey slightly more detailed information, signaling an immediate need for response. However, they generally lack specificity regarding the nature or severity of the event. For instance, fire alarms prompt immediate evacuation in response to a fire, yet they do not provide details regarding the fire's location or intensity.[60]

2. Functions indicating current status and progress

While sound serves a fundamental alerting purpose in certain instances, there are situations that demand a visual representation providing additional details about the conveyed information through sound. Auditory displays have been designed for various purposes, including monitoring factory process statuses,[61] displaying patient data within an anesthesiologist's workstation,[62] indicating blood pressure levels in a hospital setting,[63] and indicating telephone hold durations.[64]

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[58] Another frequently encountered notification is a doorbell sound, where the simple ring fails to specify the identity of the visitor or the reason for their arrival.

[59] Haas & Edworthy, 2006.

[60] More complex (and modern) kinds of alarms attempt to encode more information into the auditory signal. For example, families of categorical warning sounds in healthcare situations. See Sanderson, Liu, & Jenkins, 2009.

[61] See Gaver, Smith, & O'Shea, 1991; Walker & Kramer, 2005.

[62] Fitch & Kramer, 1994.

[63] M. Watson, 2006.

[64] Kortum, Peres, Knott, & Bushey, 2005.

3. Functions related to exploring data

The third category of auditory displays serves the purpose of facilitating data exploration. These are commonly referred to as "sonification" and are primarily aimed at encoding and communicating information pertaining to an entire dataset or its relevant components. Unlike status or process indicators, sonifications tailored for data exploration provide a comprehensive overview of the data within the system, as opposed to summarizing information to reflect a momentary state, as is the case with alerts and process indicators. However, certain auditory displays, such as soundscapes,[65] amalgamate features of both status indicators and data exploration functionalities.

4. Functions related to art, entertainment, and sport

Auditory interfaces have undergone prototyping and exploration within the realm of exhibitions, as well as recreational and fitness pursuits. Instances of audio-only adaptations have emerged for traditional games like the Towers of Hanoi,[66] and Tic-Tac-Toe,[67] extending to more intricate gaming genres such as arcade classics (e.g., space invaders),[68] and role-playing games,[69] now available in auditory formats. Additionally, auditory displays have been leveraged to enhance the involvement of visually impaired individuals in team sports. For instance, Stockman (2007) devised an audio-exclusive computerized soccer game aimed at fostering collaborative play among both blind and sighted participants. Furthermore, sonifications have recently demonstrated utility as real-time biofeedback mechanisms in competitive sports such as rowing,[70] and speed skating.[71]

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[65] Mauney & Walker, 2004.

[66] Winberg & Hellstrom, 2001.

[67] Targett & Fernstrom, 2003.

[68] See McCrindle & Symons, 2000.

[69] Liljedahl, Papworth, & Lindberg, 2007.

[70] Schaffert, Mattes, Barrass, & Effenberg, 2009.

[71] Godbout & Boyd, 2010.

Auditory interfaces have emerged as a method for providing visually impaired individuals with a comparable experience to dynamic exhibits. A framework has been devised to utilize sonified soundscapes to depict the fluid motion of fish within an "accessible aquarium”.[72] Computer vision and other sensing technologies monitor the actions of entities within the display, converting these actions into musical renditions instantly. For instance, diverse fish could correspond to distinct musical instruments. The position of each fish could be depicted through spatial sound effects, while its velocity could be portrayed through variations in tempo. Utilizing soundscapes in interactive exhibits not only renders such encounters inclusive for visually impaired individuals but also enriches the experience for sighted observers. Research conducted by Storms and Zyda (2000) demonstrated that superior audio quality enhances the perceived quality of simultaneous visual presentations within virtual environments. Further investigation is necessary to ascertain whether the inclusion of high-quality auditory displays in dynamic exhibits enhances perceived quality in comparison to solely visual experiences.

Apart from the functions of sonification outlined earlier, datasets can serve as the inspiration for musical pieces. In this scenario, composers aim not only to communicate information to the listener through these sonifications but also to evoke certain emotions or experiences. It is important to establish a systematic approach when mapping data to sound in musical compositions. Typically, these compositions incorporate a blend of sonified sounds along with traditional musical elements. For instance, Quinn has utilized data sonifications as the basis for ambitious musical projects, even producing entire albums of compositions.[73] The potential subtle distinction between sonification and music's role in conveying information remains a topic of debate,[74] as discussed by Vickers and Hogg in their influential work on the parallels between sonification and music.[75]

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[72] Walker, Godfrey, Orlosky, Bruce, & Sanford, 2006a; Walker, Kim, & Pendse, 2007.

[73] Quinn 2001 & 2003.

[74] See Worrall, 2009a.

[75] Vickers and Hogg, 2006. Also see chapter 4 of this thesis.

2.1.2.2: Approaches to Sonification

Another method of categorizing and classifying sonifications is by delineating them based on their approach to sonification. De Campo (2007) introduced a sonification design map (refer to Figure 3) outlining three overarching classifications of sonification approaches: Event-based, Model-based, and Continuous.

De Campo's (2007) methodology proves valuable as it incorporates the majority of non-speech auditory displays within a structured design context. The attractiveness of De Campo's method lies in its arrangement of diverse auditory interfaces along spectrums, facilitating fluid delineation between categories, and providing some direction in selecting a sonification method. Once more, the delineations defining taxonomic classifications of sonifications are nebulous and frequently intersecting.

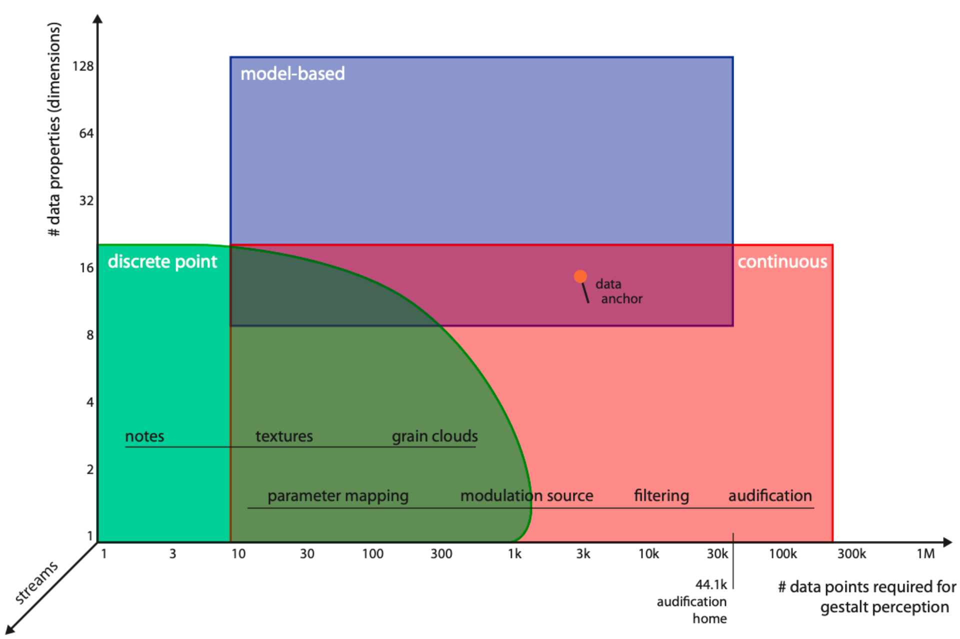

Figure 3: *The Sonification Design Space Map.*

Ways of Interactions in Sonification

Before delving into discussions about sonification approaches, it is crucial to understand the nature of interaction available to users of auditory displays. Interactivity can be seen as a spectrum along which various displays can be categorized, ranging from completely non-interactive to entirely user-driven. This understanding provides the foundation for exploring sonification effectively.

For instance, in certain scenarios, the listener may passively engage with a display without the option to actively manipulate it (e.g., controlling the pace of presentation, pausing, fast-forwarding, or rewinding). The display is initiated and plays through entirely while the user listens. This non-interactive form has been labeled as "concert mode"[76] or "tour based" sonification.[77] Conversely, the listener may have the ability to actively influence the sonification presentation. In some instances, users may select and modify displays parameters.[78] Sonifications leaning toward this interactive aspect are termed as "conversation mode"[79] or "query based"[80] sonification. Alternatively, user input and interaction may serve as the essential driver for sound presentation in certain cases.[81]

de Campo (2008) outlines various ways of interacting with sonification, i.e. approaches to sonification:

1. Event-based sonification using parameter mapping technique:[82]

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[76] Walker & Kramer, 1996.

[77] Franklin & Roberts, 2004.

[78] See Brown, Brewster, & Riedel, 2002.

[79] Walker & Kramer, 1996.

[80] Franklin & Roberts, 2004.

[81] See Hermann & Hunt, 2005.

[82] See chapter 3 "sonification techniques" for information about *Parameter mapping*.

The term “event-based"[83] denotes sonification techniques that produce sound in response to specific data events or changes. These events can be discrete incidents or alterations that trigger particular auditory signals or alerts. For instance, an event-based sonification may emit a sound when a predetermined threshold in the data is surpassed or when a specific event unfolds. Each data point corresponds to a distinct sound event. In this method, individual events or data points prompt unique sounds or sound patterns, facilitating the identification and comprehension of data alterations or occurrences. For instance, in a stock market data sonification, each fluctuation in a stock's value might elicit a distinct sound. Similarly, in environmental monitoring, diverse environmental occurrences like temperature spikes or variations in noise levels could each be represented by their corresponding sound. Typically, these sonification techniques involve passive engagement, where users predominantly listen without actively manipulating the interface. While some event-based sonifications, such as alerts, are brief and offer limited user interaction, others, like auditory graphs employing parameter mapping for data exploration, could incorporate a blend of passive listening and active user engagement.

2. Model-based sonification:[84]

Users have the capability to engage with data mappings, enabling real-time manipulation of parameters rather than passively listening to a static representation of the data.[85] Unlike event-based approaches, model-based sonification (MBS) involves the creation of a virtual model instead of directly linking data parameters to sound. This virtual model dynamically responds to user interactions based on the underlying data, functioning akin to a virtual instrument or object that users can actively interact with. The sounds produced reflect the data-driven responses to user actions, allowing users to gain insights into the data's structure through its acoustic feedback. MBS heavily relies on user interaction to shape the sounds and is adept at handling large volumes of data and intricate data points. Examples of such models include Shoogle,[86]

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[83] For more information about “event-based” see chapter 2, section 1.2.9.

[84] See chapter 3 “sonification techniques” for more information about *Model-based sonification*.

[85] See Hermann & Hunt, 2004.

[86] Williamson, J., Murray-Smith, R., & Hughes, S., 2007.

which turn text messages into sound via shaking, the Local Heat[87] exploration model, and Data bubbles.[88]

3. Continuous sonification:

"Continuous" signifies the uninterrupted conversion of data into auditory signals. In instances involving high sampling rates, such as with seismic data,[89] data can be rendered into waveforms using a method termed audification.[90] Gregory Kramer, in his work "Auditory Display," offers the following definitions: “The direct playback of data samples I refer to as ’audification’.”[91] Subsequently, he revises this definition, describing edification as “the direct translation of a data waveform into sound.”[92] The resulting waveforms from audification may sound unconventional as they do not adhere to the “physical laws that exist in nature”,[93] posing challenges for users in interpretation.[94] Nevertheless, these distinctive waveforms have the potential to stimulate creative sound design and composition.[95]

While previous discussions have generally categorized sonifications based on their function or technique, the distinctions between these categories are often unclear. Additionally, the function of the interface within a system may limit the techniques that can be employed for sonification, and conversely, the chosen technique may restrict the functions that the interface can fulfill. Event-driven approaches are primarily utilized for alerts, notifications, alarms, and monitoring status or processes, as these functions are typically triggered by events within the monitored

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87 Bovermann, T., Hermann, T., & Ritter. H., 2005. See https://pub.uni-bielefeld.de/record/2699962

88 Milczynski, M., Hermann., T., Bovermann, T., & H. Ritter., 2006. See https://pub.uni-bielefeld.de/record/2700564

89 See Bioacústiques, 2010.

90 See chapter 3 “sonification techniques” for information about *Audification*.

91 Kramer,G., 1994. p. xxvii.

92 Walker, B., & Kramer, G (2004), p.152.

93 Van Ransbeeck, 2018.

94 Worrall, 2009.

95 For some examples see Chapter 3, Section “3.1.2.1: Artistic Examples Using Audification” of this thesis.

system. Depending on the specific task of the user, data exploration may involve event-driven methods, model-based sonification, or continuous sonification techniques.[96]

After identifying the type of data and the objective at hand, the process of constructing a sonification entails mapping the data source(s) into auditory variables that represent them. This is particularly crucial for techniques like "parameter mapping," but it applies broadly to all sonification methods. The mappings selected by the designer or artist aim to convey information within each acoustic dimension employed. It's also essential to evaluate the extent to which the listener grasps the ‘intended message' and how closely the perceived information aligns with the ‘intended message’.

2.1.3: Challenging Factors for Sonification: Aesthetics Consideration, Individual Differences, Importance of Training

While forthcoming studies should explore the suitability of specific tasks and datasets for auditory representation, the primary hindrances in utilizing sonifications have historically revolved around, and are likely to persist in, the perceptual and cognitive capacities of human listeners.

2.1.3.1: Aesthetics and musicality

In the realm of sonification, questions concerning aesthetics and musicality persist. While the utilization of musical sounds is often recommended due to their perceptual ease compared to simpler tones,[97] the effectiveness of employing such musical sounds, particularly those from MIDI instrument banks, in enhancing performance remains uncertain. Despite the importance of addressing aesthetic and musical concerns, it is advisable to prioritize the design of sonifications that are aesthetically pleasing, such as those with musical qualities, while ensuring effective

[96] Barrass, 1997.

[97] Brown et al., 2003.

communication of the intended message. Vickers and Hogg (2006) emphasized the significance of aesthetics in sonification, asserting that greater attention to aesthetics could enhance listening experience and comprehension of displayed information.

2.1.3.2: Individual differences and training

The effectiveness of auditory displays is influenced by various factors, including the abilities, limitations, and experiences of listeners, as well as transient states like mood and fatigue levels. Surprisingly, there is limited knowledge regarding how individual differences, both between and within individuals, affect outcomes with auditory displays. Understanding these differences in perceptual, cognitive, and musical abilities among listeners is crucial for informing the design of sonifications. Firstly, comprehending the range of individual differences allows designers to create displays that cater to most users in a given context, promoting universal design principles.[98] Secondly, in situations where optimal display users are preferred, knowledge of individual differences enables the selection of operators whose capabilities maximize the likelihood of display success. Lastly, exploring how differences in training and experience with sonifications impact display performance warrants further investigation.

2.1.4: Developing a Unified Theoretical Framework for Sonification

Contemporary studies are steering the domain of sonification towards numerous promising avenues, with scholars and professionals just beginning to explore the possibilities of utilizing sound to enrich current interfaces or even crafting entirely auditory interfaces. The body of literature on auditory displays has seen considerable expansion. Despite these achievements, the field of sonification encounters numerous hurdles and complexities in its quest for universally accessible, user-friendly, and aesthetically pleasing soundscapes for human-computer

[98] See Iwarsson & Stahl, 2003.

interactions. Arguably, the most pressing challenge lies in establishing a coherent theoretical framework that can sustain the ongoing evolution of research and design in this field.

Despite the significant contributions of interdisciplinary approaches to research and practice in auditory display, the diversity within the field has likely hindered the establishment of a coherent understanding of sound as a medium for conveying information. Currently, there is a scarcity of theories or frameworks concerning human interaction with auditory displays. It appears inevitable that the field of sonification will need to formulate more comprehensive theoretical frameworks to fully exploit its potential. As highlighted by Edwards (1989), expanding or creating new models for human interaction with information systems that encompass auditory displays will yield dual benefits: 1) in research, these models will offer testable hypotheses, guiding a systematic and methodical approach to auditory display research, and 2) in practice, designers of auditory displays will have foundational guidelines to follow. Despite these advantages, the development of theory remains challenging, particularly in fields like sonification that prioritize pragmatism and design.[99]

A differentiation has been made between the process of "theorizing" within a field and the resultant "theory" as the product of that process.[100] While there isn't a definitive overarching theory of sonification, recent advancements indicate active progress towards establishing meaningful theoretical frameworks within the discipline. Encouraging signs of advancement toward fulfilling some of the criteria for a cohesive sonification theory are emerging. The development of theory in sonification hinges on the establishment of a shared vocabulary, a topic which Hermann (2008) has recently initiated much-needed discourse regarding definitional boundaries and fundamental terminology. Effective theory necessitates a coherent organization of existing knowledge, with de Campo's (2007) recent efforts representing a significant stride towards categorizing the various sonification designs within a unified framework.

[99] For a discussion, see Hooker, 2004.

[100] Weick, 1995.

Theoretical frameworks are essential in bridging the gap between research findings and practical application. Brazil[101] has emerged as a source of valuable insights into integrating sonification design with empirical evaluation methods. These frameworks delineate the key variables influencing the performance of systems involving data display and human interaction. Nees and Walker (2007) have recently outlined a conceptual model identifying variables crucial to understanding auditory graph comprehension, while Bruce and Walker (2009) have adopted a similar approach to explore the role of audio in dynamic exhibits. Embracing theory promises to yield standardized knowledge rather than relying on individualistic, ad hoc designs. Frauenberger and Stockman (2009) have devised a framework to facilitate the documentation and dissemination of effective designs for auditory displays.

Consequently, there are grounds for optimism concerning the future trajectory of theoretical exploration in the field of sonification, with the establishment of a shared repository of organized knowledge to steer new research directions, and ensuring the effective implementation of sonifications in focus as primary goals for the field in the immediate future.

2.2: Psychoacoustics, and Sound Perception in Sonification

2.2.1: Psycho-acoustics

2.2.1.1: Introduction

Understanding auditory stimuli in real-world settings poses a significant challenge due to the intricate interplay of various sounds, often overlapping in frequency and time. Exploring the auditory system's ability to decipher this complexity involves examining sounds that carry substantial information and how our evolutionary heritage has shaped our capacity to extract such information. Considering this evolutionary framework, humans have inherited a biological

[101] Brazil, 2010; Brazil & Fernstrom, 2009.

system optimized for processing auditory input, prompting investigation into how our auditory mechanisms decode meaningful information and how this understanding can inform the effective sonification of diverse datasets.

One significant biological aspect of sound pertains to its identity, encompassing the spectro-temporal attributes enabling the extraction of pertinent information conveyed by the sound. Another crucial biological aspect concerns the localization of the sound source. In numerous situations, the appropriate response to the information carried by the sound is contingent upon its spatial relationship to the listener – whether to approach a potential opportunity or retreat from a perceived threat. All sounds reach the eardrum as a collective stream of pressure variations that collectively stimulate the inner ear. Notably, the auditory system demonstrates the remarkable ability to disentangle these diverse sound streams, enabling the selective focus of attention on specific streams.[102]

Our understanding of the intricate auditory landscape, stemming from various sources, relies on a multitude of acoustic signals perceived by each ear. Auditory processing hinges on the breakdown and encoding of this information at the auditory nerve level, followed by its integration in the brain to discern the identity and spatial attributes of distinct sources. Additionally, our ability to concentrate on specific sounds while disregarding distractions is influenced, in part, by differences in the spatial distribution of these sound sources. This capability to segregate sounds is pivotal for extracting meaningful insights from the complex auditory milieu we encounter. (See media file #1)

In the realm of auditory presentations, it is crucial to align the fidelity of a display with the encoding capacity of the human auditory system. Understanding how the auditory system processes changes in sound is pivotal in designing such displays. For instance, if a designer opts to convey information through alterations in sound frequency or amplitude, they must consider the auditory system's sensitivity to these physical attributes to ensure perceivability. In real-world listening scenarios, multiple factors influence the perception of individual sound sources, making

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[102] Bregman, 1990; Cooke and Ellis, 2001.

perception a complex process that doesn't necessarily follow a straightforward combination of frequency components.

Another crucial concern involves comprehending how various elements in a sound environment are perceived collectively to form distinct perceptual entities and how alterations in the sound's physical attributes impact these entities differently. For instance, in the development of a 3D audio interface, one pivotal aspect is creating a realistic acoustic environment. However, less apparent features of the interface might also significantly influence user experience. For instance, introducing reverberation into the interface could notably enhance the sensation of "presence" or the impression of being immersed in a virtual auditory environment.[103] On the other hand, reverberation could impair users' ability to accurately locate brief sounds.[104]

2.2.1.2: The Auditory System in Humans

The initial step in the process of sound perception involves the transformation of physical acoustic energy into biological signals within the inner ear. This conversion mechanism dictates the encoding and transmission properties that govern our perception of sounds in the external environment. Consequently, sound is not merely encoded but may undergo filtration of different aspects. Sound enters the auditory system via the outer and middle ears before being transduced into biological signals within the inner ear. Throughout this passage, the sound undergoes various transformations.

The human auditory system comprises three primary divisions: the outer, middle, and inner ear. Sound is first collected and filtered by the pinna and concha of the outer ear, then conveyed to the middle ear through the external auditory canal. Within the middle ear, sound transitions from the gaseous medium of the outer ear to the fluid medium of the inner ear. In the inner ear, physical sound energy is converted into biological signals, which are transmitted to the brain via

[103] Durlach et al., 1992.

[104] For examples see Giguere and Abel;1993. & Braasch and Hartung; 2002.

the auditory nerve. The neural impulses originating from each ear constitute the fundamental biological mechanism underlying our perception of various auditory characteristics.[105]

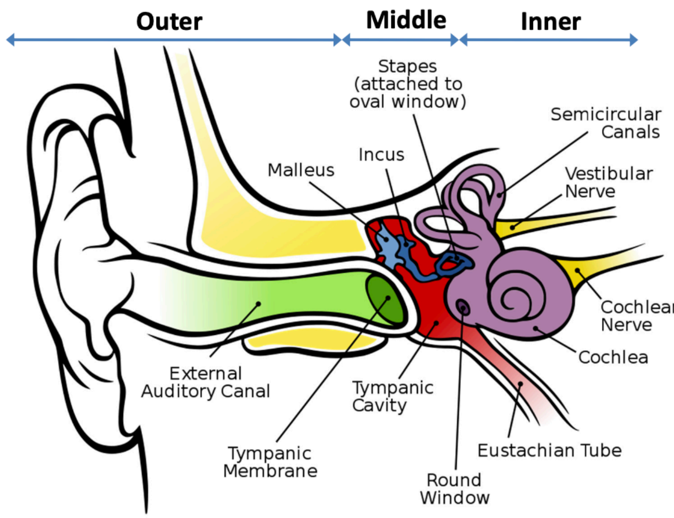

Figure 4: *Converting mechanical sound energy into biological signals within the auditory nervous system*

2.2.1.3: Conclusion

The sonic environment encompasses objects characterized by perceptual attributes like pitch, timbre, loudness, spatial location, and duration. Biologically significant information is conveyed through temporal variations in these attributes. Sound is transmitted and filtered from the surrounding air to the inner ear by the outer and middle ears. Within the inner ear, the cochlea transforms sound into biological signals. The frequency components of sound are decoded into a spatially organized pattern on the basilar membrane, which then transmits signals in a structured manner through the auditory nervous system to the auditory cortex. Additionally, temporal encoding, especially for low to mid frequencies, contributes to maintaining high sensitivity to frequency distinctions within this range.

[105] S. Carlile, 1996.

The auditory system interprets various attributes of sound, such as loudness, pitch, timbre, and spatial location, from the sequence of biological signals produced in the auditory nerve. These signals are organized into auditory objects and streams, facilitating the recognition of distinct sound sources. Spatial location is determined by analyzing acoustic differences between the ears, including variations in sound level and arrival time, as well as the ear's filtering of sound frequencies. By processing these cues, the auditory system can accurately perceive the direction and distance of sound sources relative to the head. Additionally, movement of sound sources or changes in spectral characteristics can induce perceptual effects related to motion.

2.2.2: Perception of Sound in Sonification

Perception typically operates effortlessly and involuntarily. The sensory input from light and sound in our environment undergoes rapid neural processing, resulting in our subjective experience of the visual and auditory world around us. Despite the apparent ease and speed of this process, it conceals the intricate workings of the underlying mechanisms. Consequently, there's a tendency to undervalue the significance of studying perception and cognition, especially in practical settings such as auditory display design.

The significance of perception in sonification has been a subject of historical contention. In 1997, during a workshop on sonification organized by the International Community for Auditory Display (ICAD) and sponsored by the National Science Foundation, a report titled "Sonification Report: Status of the Field and Research Agenda"[106] was produced. A primary objective of the working group was to formulate a precise definition of "sonification." The debate and initial disagreement regarding the inclusion of aspects related to "perception" in the definition of sonification highlighted the undervaluation of perception's role in the field. Following deliberation, the group eventually settled on the subsequent definition: "[…] sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation." The incorporation of terms like "perceived

[106] Kramer, et al., 1999.

relationships" and "communication or interpretation" underscores the significance of perceptual and cognitive mechanisms in crafting effective auditory representations. While perception is often seen as effortless and automatic, it is a complex and non-trivial process. If the objective of auditory representation is to convey meaning through sound, understanding the perceptual mechanisms that attribute meaning to sound becomes indispensable.

Equally significant are the cognitive elements implicated in deriving significance from an auditory presentation and the user's actions, as well as the interactions the user engages in with the display interface. Extensive research indicates that interaction, or the anticipated interaction with a stimulus, like an auditory display, can impact perception and cognition. Hence, comprehending the perceptual capacities, cognitive operations, and behaviors of the user is imperative in crafting efficient sonifications.

2.2.3: Perception of Sound: Mapping Data to Auditory Dimensions

There exist numerous methods to characterize a sound. One may delineate the sound of an oboe based on its timbre, the speed of note generation, or its spatial location. These attributes collectively fall under the umbrella of "auditory dimensions." An auditory dimension is typically construed as the subjective perceptual encounter of a specific physical attribute of an auditory stimulus. For instance, a fundamental physical attribute of a tone is its fundamental frequency, usually quantified in cycles per second or Hz. The perceptual dimension primarily corresponding to the physical dimension of frequency is known as "pitch," indicating the apparent "highness" or "lowness" of a tone. Similarly, the physical magnitude of a sound (or its amplitude) serves as the primary determinant of the auditory dimension "loudness".

A common strategy employed by designers of auditory displays involves utilizing various dimensions as "channels" to convey multidimensional data. For instance, in a sonification of real-time financial data, Janata and Childs (2004) utilized rising and falling pitch to signify fluctuations in the price of a stock, while loudness indicated proximity to a predetermined target, such as its thirty-day average price. Nonetheless, as discussed in the preceding section on psychoacoustics, this task is notably intricate because there isn't a straightforward correspondence between the physical attributes of a stimulus and its perceptual counterparts. Additionally, in the auditory realm, there is a dynamic interplay among different dimensions; for instance, the pitch of a sound can influence its perceived loudness, while loudness can reciprocally affect pitch. Moreover, factors like timbre and duration can also exert mutual influences. This aspect gains significance in auditory displays, where various auditory dimensions often represent different variables within datasets. The intricacies of these interactions among auditory dimensions remain largely unexplored within the research community, particularly regarding their impact on practical tasks like those encountered in auditory displays. However, among the auditory dimensions commonly employed in sonification —pitch, loudness, and timbre—there is a need for deeper investigation into their nuanced relationships and effects.

2.2.3.1: Pitch

Pitch is frequently employed as the primary auditory dimension in sonification, and indeed, it is unusual to encounter a sonification devoid of pitch variations. Utilizing pitch offers several advantages, as it can be easily manipulated and correlated with data alterations. The human auditory system is highly sensitive to pitch changes, capable of discerning differences of less than 1Hz at a frequency of 100Hz. Furthermore, the use of musical scales in auditory displays can provide a familiar cognitive framework for presenting information, particularly when discrete notes represent different data values.

Nonetheless, there are some drawbacks to utilizing pitch. Certain research indicates that individual variations in musical aptitude may influence the perception of displays employing pitch modulation.[107] Even in the early stages of psychophysics, it was recognized that the perception of pitch could be influenced by musical context. Eminent psychophysicist S.S. Stevens, for instance, regarded the intrusion of musical context into the psychophysical examination of pitch as an extraneous factor. He endeavored to use participants with limited

[107] Neuhoff, Kramer, & Wayand, 2002.

musical exposure and introduced control measures aimed at preventing the establishment of a musical context by the participants. For instance, rather than employing frequency intervals that corresponded to those of a musical scale (such as piano notes), he utilized intervals that avoided any alignment with musical scales.

In discussing the complexities of developing the mel scale, a perceptual measure where pitches are perceived as equally spaced, Stevens noted “The judgment is apparently easier than one might suppose, especially if one does not become confused by the recognition of musical intervals when he sets the variable tone.”[108] Stevens and colleagues recognized the presence of special relationships between musical intervals affecting pitch perception. Essentially, frequency intervals aligned with those in music hold more significance and are more noticeable than others, especially for listeners with musical training. This aspect is crucial to consider in sonifications aimed at artistic creation.

When a display designer or a sonification artist intends to utilize pitch changes, these changes must be logically correlated to specific data variations. The issue of how to map the direction of pitch change (whether ascending or descending) to rising or falling data values is referred to as "polarity." Intuitively, it might seem appropriate to represent increasing data values with rising pitch. Indeed, many sonification projects have adopted this "positive polarity" approach. For instance, in sonifying historical weather data, daily temperature is often mapped to pitch, where higher frequencies correspond to higher temperatures and lower frequencies to low temperatures.[109] However, this correlation between data values and pitch is not universally applicable and can vary depending on the type of data and the user's characteristics. For instance, when sonifying size, a "negative polarity" where decreasing size is represented by increasing pitch might be more effective.[110]

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[108] Stevens & Davis,1938, p. 81.

[109] Flowers, Whitwer, Grafel, & Kotan, 2001.

[110] The cognitive mechanisms that underly polarity relationships between data and sound have yet to be investigated. See Walker, 2002.

Walker and colleagues[111] have extensively investigated the most suitable polarity and conceptual associations between data and sound dimensions. Their research highlights the intricate nature of mapping pitch to data dimensions, particularly regarding polarity. Different data dimensions, such as temperature, size, and pressure, exhibit varying effective polarities, and individuals display significant variation in their preferred polarities. Some users exhibit inconsistent preferences for polarity, while in other cases, distinct individual differences can predict preferred polarities. For instance, visually impaired users may prefer a different polarity compared to those without visual impairment.[112] This reveals that what might appear to be a straightforward auditory dimension for use in displays actually involves unexpected complexity. The influence of musical context also varies among users. Therefore, mapping data to pitch changes requires careful consideration of these factors during the design process.

2.2.3.2: Loudness

Loudness is a perceptual characteristic that corresponds to the amplitude of an acoustic signal. Although changes in loudness are not as commonly used as pitch changes in auditory displays, they are still widespread. The main benefits of utilizing loudness changes in auditory displays include their ease of manipulation and the general user comprehension. However, despite its widespread application, loudness is typically regarded as an inadequate auditory dimension for representing continuous data sets. There are several significant limitations to using loudness changes for indicating data variations in sonification and auditory displays.

Firstly, while there is a clear ability to distinguish between sounds of varying intensities, this ability does not match the precision seen in differentiating between sounds of different frequencies. Secondly, memory for loudness is notably poor, especially when compared to the more reliable memory for pitch. Thirdly, the variability in background noise and the sound reproduction equipment used in any auditory display can differ significantly based on the user’s

[111] Walker 2002; Walker 2007; Smith & Walker, 2002; Walker & Kramer, 2004.

[112] Walker & Lane, 2001.

environment, complicating the reliable sonification of continuous variables through changes in loudness. Finally, there are no inherent cognitive frameworks for loudness akin to the musical scales available for pitch. Additionally, loudness, like most perceptual dimensions, can interact with other dimensions such as pitch and timbre.[113]

Loudness variation is frequently employed in auditory displays, and when applied correctly in suitable contexts, it can be highly effective. The most impactful use of loudness variation typically happens when it is limited to two or three distinct levels, corresponding to two or three specific states of the sonified data. This approach allows discrete loudness changes to signify categorical shifts in a variable's state or to denote when a variable meets a specific criterion. Continuous loudness adjustments can represent data trends. However, perceiving absolute data values solely through loudness changes is challenging. Conversely, continuous loudness variation can be combined with pitch changes to increase the prominence of significant data changes or auditory alerts.

2.2.3.3: Timbre

Timbre is the perceptual dimension about which we possess the least psychophysical understanding. Even providing a precise definition of timbre has proven to be quite challenging. The most frequently referenced definition, provided by the American National Standards Institute (ANSI), essentially describes timbre by exclusion, specifying what it is not, and implying that what remains is timbre. ANSI's "negative definition" of timbre states that it is "that attribute of auditory sensation in terms of which a listener can judge that two sounds, similarly presented and having the same loudness and pitch, are different." In simpler terms, timbre is the quality that enables us to distinguish between a trumpet and a clarinet when both are playing the same note at the same volume.

The challenge in defining timbre arises from the absence of a definitive physical characteristic that accounts for its perception. Unlike the straightforward physical-perceptual correlations seen

[113] Flowers, 2005.

with amplitude-loudness and frequency-pitch, timbre lacks a single dominant physical attribute that directly corresponds to it. Although the spectral profile of sound is frequently cited as a key factor in timbre perception, and spectrum indeed plays a role, the dynamic aspects of the amplitude envelope—such as the attack, sustain, and decay times—also significantly impact the perception of timbre.

Timbre serves as a powerful auditory dimension for sonification and has been utilized in both continuous and categorical forms. For instance, continuous variations in timbre have been suggested for use in the auditory guidance of surgical tools during brain surgery.[114] In this scenario, spectral changes indicate variations in the surface over which the surgical tool moves. When the tool traverses a uniform surface, the spectrum remains consistent, but it changes abruptly in response to surface heterogeneity. Conversely, discrete changes in timbre, such as using different musical instrument sounds, can effectively represent various data variables or states.

Won utilized distinct timbral variations to convey the extent of confirmed gene information in a sonification of the human chromosome.[115] Gene sequence maps usually employ six colors to indicate the level of confirmed genetic knowledge. In this work, Won used six different musical instruments to symbolize the varying degrees of knowledge. It is crucial to select timbres that are easily distinguishable when employing different timbres. Sonification with similar timbres can cause confusion due to unwanted perceptual grouping.[116]

2.2.4: Mapping Data: Interaction of Auditory Dimensions

At first glance, one might assume that distinct changes in individual acoustic properties of a stimulus, such as frequency, intensity, and spectrum, would be perceived as unique

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[114] Wegner, 1998.

[115] Won, 2005.

[116] Flowers, 2005.

characteristics of a sound. However, growing evidence suggests otherwise. Alterations in acoustic dimensions impact not only the perception of the corresponding dimension but also specific characteristics of other perceptual dimensions. For example, a change in pitch can influence the perception of loudness. This dimensional interaction has significant implications for sonification and auditory displays. The challenge of interacting perceptual dimensions has been addressed by mapping multiple perceptual dimensions (e.g., pitch and loudness) to a single data variable, thereby enhancing the salience of data changes. This method is particularly effective for highlighting important signals. Depending on the display context, dimensional interaction can be either beneficial or detrimental for auditory displays.[117]

In the realm of sonification and auditory display, it is common practice to employ various auditory dimensions to represent different variables within a dataset. For instance, when translating historical weather patterns into sound, a designer might assign pitch changes to temperature fluctuations, loudness variations to precipitation levels, and timbre shifts to changes in humidity. These variations in weather variables can be effectively conveyed through alterations in three distinct acoustic signal characteristics: frequency, amplitude, and spectrum. However, the perceptual interaction between these dimensions can pose challenges. Despite loudness primarily being determined by sound amplitude, research suggests that frequency can subtly influence loudness perception. Fletcher and Munson (1933) demonstrated that the loudness of equally intense pure tones varies with frequency, as evidenced by their "equal-loudness contours," highlighting human sensitivity to sounds within certain frequency ranges. Similarly, Stevens (1935) illustrated that intensity can affect pitch perception through his "equal-pitch contours," revealing that tones differing in intensity can still be perceived as equal in pitch despite slight frequency variations. Timbre, likewise, can interact with pitch and loudness in comparable manners.

Utilizing auditory dimensions can have drawbacks when distinct variables are assigned to different auditory dimensions. Nonetheless, there are instances where leveraging the interaction of auditory dimensions can be advantageous in sonification. Research indicates that associating a

[117] Anderson & Sanderson, 2009; Melara & Marks, 1990; Neuhoff, Kramer & Wayand, 2002, Walker & Ehrenstein, 2000.

single variable with multiple auditory dimensions enhances the perceptibility of changes in that variable compared to mapping it to single dimensions alone. For instance, in representing fluctuations in internet traffic volume on a specific site, one might use variations in loudness to signify changes in traffic volume, with increased loudness indicating higher traffic volume. However, research by Hansen and Ruben (2001) demonstrated that perceptual salience could be heightened by redundantly mapping traffic changes to multiple dimensions. They illustrated an increase in traffic by linking it to changes in loudness, timbre, and repetition rate of a tone. Thus, an increase in traffic would produce a tone that not only increases in loudness but also exhibits brighter timbre and faster repetition rate. This form of "redundancy mapping" proves effective in situations where relative changes and trends hold greater significance than absolute data values.

Redundancy mapping proves beneficial in monitoring auditory processes, especially in scenarios where visual attention is occupied. For instance, Peres and Lane (2005) demonstrated that redundant mapping of pitch and loudness enhanced performance in tasks where listeners had to monitor auditory representations alongside visual tasks. Notably, the performance improvements attributed to redundancy mapping were observed solely for auditory dimensions that exhibit interaction or are deemed "integral," such as pitch and loudness. Conversely, when redundant mapping was applied to "separable" auditory dimensions, such as pitch and tempo, performance did not surpass that of utilizing a single auditory dimension.

2.2.5: Auditory-Visual Interaction in Sonification

Perceptual research has historically shown a bias towards investigating vision over audition, often focusing on singular sensory modalities rather than exploring their interplay. Detailed understandings of the functioning of visual pathways surpass those of auditory structures. Additionally, limited knowledge exists regarding the physiological interplay between these sensory systems. Nonetheless, notable instances of auditory and visual interaction exist on both neurological and behavioral fronts, with significant implications for auditory displays. One renowned case of such interaction is evident in the realm of speech perception.

The "McGurk Effect" arises when there is a disparity between visual and auditory speech stimuli presented simultaneously. For instance, individuals may watch a video of someone pronouncing the syllable /ba/ while hearing the audio for /ga/. Consequently, observers frequently perceive the syllable as /da/ (refer to media file #2). This research offers compelling support for the concept of multimodal speech perception, corroborated by studies demonstrating enhanced speech intelligibility when individuals can both see and hear the speaker. Thus, although auditory displays are typically advantageous in situations where visual attention is occupied or in low vision scenarios, incorporating video into auditory displays, particularly those involving speech, may enhance their reliability under suitable conditions.[118]

2.2.6: Space as a Dimension for Sonification

Utilizing the capacity to perceive sound spatially and detect its motion holds promise for integrating auditory presentations in both physical and virtual settings. The incorporation of spatial dimensionality offers intriguing avenues for designers of sonification and auditory displays. Technological advancements in recent times have spurred an increased adoption of spatialized sound in the realms of sonification and auditory display.

As exemplified by Brungart and Simpson (2008), an innovative auditory interface was developed for pilots to convey the aircraft's orientation relative to the horizon, encompassing both plane’s pitch and roll. Spatial representation of roll adjustments was achieved by dynamically shifting an audio signal between the left and right headphones in response to lateral tilting of the plane. Meanwhile, alterations in pitch were communicated through spectral filtering, with a low-pitched and diffuse quality denoting a nose-up position, and a high-pitched characteristic indicating a

[118] Munhall, Jones, Callan, Kuratate, & Vatikiotis-Bateson, 2004; Sumby & Pollack, 1954.

nose-down attitude. Opting for any audio input, including music preferred by the pilots, allowed for increased user comfort and compliance with the system, minimizing annoyance and listener fatigue.

2.2.7: Rhythm and Time as Dimensions for Sonification

Auditory display is highly advantageous in fields where the perception of rhythm and the discernment of time intervals are crucial, especially when the data being conveyed naturally exhibit rhythmic or temporal variations. This is especially effective when the presentation rate aligns with the user's optimal sensitivity range for tempos.[119]

The temporal aspect of sound is fundamental, and studies have extensively explored variations in the timing and pace of acoustic signals. Effective communication of relevant information can be achieved through disparities in tempo between presentations and alterations in tempo within a single presentation. For instance, heightened urgency is generally perceived when auditory stimuli are delivered at accelerated rates.[120] While changes in tempo can also signal directional information (e.g., "up," "down"), tempo as a directional cue may be comparatively less robust than similar alterations in pitch and loudness.[121] The semantic connotations of rapid and slow rhythmic tempos have been investigated within the domain of earcons.[122] Moreover, sensitivity to rhythm can serve to indicate processes or anomalies in data. For instance, Baier, Hermann, and Stephani utilized rhythm variations to differentiate between epileptic and non-epileptic activity in human EEG data.[123] Furthermore, modifications in rhythm and tempo have been applied in biofeedback systems tailored for stroke rehabilitation.[124]

[119] Jones, 1976; Jones & Boltz, 1989.

[120] Edworthy, Loxley, & Dennis, 1991; Langlois, Suied, Lageat & Charbonneau, 2008.

[121] Pirhonen & Palomäki, 2008.

[122] Palomäki, 2006.

[123] See media file #6 in chapter 2 (EEG), Stephani 2007; Baier & Herman, 2004.

[124] Wallis, et al. 2007.

2.2.8: Auditory Environments: Implications for Sonification

Sounds typically occur amidst multiple concurrent sound sources, each generating distinct acoustic waves that reach the ear simultaneously. It's uncommon to encounter singular sounds in most environments; for instance, the whir of a computer fan coexists with the ticking of a clock, distant conversations, and the muted rumble of passing vehicles. Despite this sonic complexity, listeners effortlessly discern individual sources, distinguishing where one sound ends and another begins. This ability to parse auditory inputs has significant implications for sonification. By leveraging listeners' capacity to attend to separate sources or auditory streams, designers can capitalize on our perceptual organization abilities. This allows for the presentation of various facets of multidimensional data through distinct auditory channels simultaneously.

Acoustic properties and factors related to attention both play roles in how the auditory system organizes what is perceived within an auditory environment. On the acoustic side, individual sound sources exhibit specific regularities in their emitted sounds, which the auditory system utilizes to distinguish between different auditory streams. For instance, sounds with similar frequencies tend to be perceived as originating from the same source. Consequently, when sonifying a dataset with multiple dimensions, it's customary to differentiate various variables by employing distinct frequency ranges. One variable might be conveyed through low-frequency sounds while another through high-frequency ones. This separation in frequency enhances the likelihood of maintaining independence between the sonified variables. Likewise, sounds with similar timbres are more likely to be perceived as belonging together. Hence, a prevalent approach involves using different musical instruments to represent distinct aspects of the underlying data.

Pitch and timbre variables can be independently manipulated to influence auditory grouping dynamics. For instance, the grouping effect facilitated by pitch similarity can be mitigated by introducing timbral dissimilarities, vice versa.[125] Conversely, enhancing the grouping effect can be achieved by incorporating redundant segregation cues within each auditory stream. For instance, disparities in both pitch and timbre between a bass guitar and a piccolo would yield superior stream segregation compared to solely relying on timbral distinctions, such as those between a saxophone and trumpet played within the same frequency range. Moreover, distinctions in other acoustic attributes like loudness and spatial positioning can also aid in segregating sound sources. While loudness level may not exert as significant an influence on grouping as other acoustic attributes, sounds presented at comparable levels still tend to cluster together.[126] Spatial position serves as a robust determinant for segregating auditory streams. Sounds originating from the same spatial location typically coalesce. Conversely, a lack of spatial consistency often impedes the perceptual grouping of sounds. For instance, a series of tones delivered to alternating ears usually fails to form a unified auditory stream.[127] Utilizing binaural cues for spatial separation of sources proves to be an especially effective strategy for segregating real-world sources, such as multiple speakers.[128]

2.2.9: Cognitive Representations in Sonification

The concept of cognitive representations of stimuli has a significant background in cognitive psychology and holds promise for designers of auditory displays. Surprisingly, there has been limited utilization of cognitive representations of real-world sounds by sonification designers for representing diverse datasets. Instead, many rely on basic alterations in pitch, volume, or tone to reflect changes in the variables of interest. Consequently, the resulting auditory signals often lack a direct cognitive link to the underlying data for the listener. While it is possible for individuals to learn associations between the changing acoustic features and the dataset, this understanding typically occurs as a secondary process. For instance, recognizing that a shift in tone signifies a

[125] Singh, 1987.

[126] Hartmann & Johnson, 1991; Van Noorden, 1975.

[127] Van Noorden, 1975.

[128] Hawley, Litovsky, & Culling, 2004.

change in temperature. Additionally, when sonifying multivariate datasets, designers frequently incorporate simultaneous modifications in pitch, volume, and tone within a single signal to represent various data changes. However, such approaches may lead to distortions in the underlying data due to perceptual interaction effects.

An alternative method to sonification has been proposed, suggesting the mapping of changes in real-world auditory occurrences to alterations in the underlying dataset. Gaver (1993) proposed that listeners focus on "auditory events" in a manner that assigns significance to the physical attributes of the sound source in the auditory perception of non-verbal sounds. Thus, instead of perceiving "[…] a quasi-harmonic tone lasting approximately three seconds with smooth variations in the fundamental frequency and the overall amplitude […]," listeners would instead describe hearing "A single-engine propeller plane flying past."[129] Consequently, listeners consciously interpret events rather than focusing on the acoustic characteristics.

Neuhoff and Heller (2005) proposed that employing an "event-based" representation could be beneficial in sonification. Instead of directly correlating rising pitch with data increments, designers could link data fluctuations to the rhythm of a familiar real-world auditory event, like footsteps.[130] which listeners adeptly perceive. This method offers a dual advantage. Firstly, alterations in intricate stimulus dimensions are typically more recognizable and straightforward to discern compared to alterations in basic acoustic dimensions. Secondly, the issue of undesirable overlapping perceptual dimensions can be circumvented by employing real-world auditory occurrences to portray changes in data. For instance, if velocity of movement were utilized to depict one factor in a multifaceted dataset, the solidity of the surface could be employed to depict another factor. The majority of listeners are capable of distinguishing specific attributes of walking surfaces alongside characteristics of the walker, such as gender and stature.[131]

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[129] Gaver, 1993, p. 285–286.

[130] Li, Logan, & Pastore, 1991; Visell, et al., 2009.

[131] Visell, Fontana, Giordano, Nordahl, Serafin& Bresin, 2009.

2.2.10: Musical Elements and Sonification

Musical systems represent highly organized auditory cognitive structures. Musical scales offer a structured framework that can be utilized in designing effective auditory displays.[132] Therefore, since the primary objective of auditory displays is information communication, integrating insights from music theory can enhance their design. Instead of associating data with arbitrary frequency shifts, many auditory displays link data variations to pitch alterations constrained within culturally recognized musical scales. For instance, Vickers and Alty utilized melodic patterns to assist computer programmers in debugging code and offering programming feedback.[133] Similarly, Valenzuela (1998) utilized melodic elements to furnish users with integrity assessment data concerning concrete and masonry structures.

One benefit of employing musical scales in sonification lies in their potential to be perceived as more enjoyable and less bothersome compared to frequency alterations not confined to musical scales. While extensive research has demonstrated that varying degrees of musical proficiency[134] can impact perceptual abilities within a musical context,[135] these variances can be mitigated when the stimuli are interpreted using units that mirror the underlying data dimensions.[136]

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[132] Krumhansl, 1982; Jordan & Shepard, 1987; Shepard, 1982.

[133] Vickers & Alty, 1997; 2002; 2003.

[134] The impact of musical proficiency on the interpretation of auditory presentations remains largely unexplored. One of the challenges in this field stems from the absence of a meticulously developed framework for assessing musical expertise (Edwards, Challis, Hankinson & Pirie, 2000).

[135] E.g., Bailes. 2010

[136] Neuhoff, Knight, & Wayand, 2002.

Chapter 3 - Sonification Techniques

3.1: Audification

3.1.1: Introduction

Music is transient, briefly entering reality before quickly vanishing. It has a form that unfolds over time but lacks physical tangibility. This inherent transience makes archiving music challenging, and two primary methods have been developed to address this: (i) the score, which serves as a coded set of instructions for performers or sound generators to recreate the music later,[137] and (ii) the recording, which captures sound waves at a specific listening moment, analogous to photography. Each method has its pros and cons as they cannot perfectly replicate the original sound, but they each offer unique perspectives and reveal aspects that might otherwise go unnoticed. The score emphasizes the symbolic value of tones, while the recording captures the exact physical sound wave in an analog manner. These two perspectives are also present in sonification: (i) parameter mapping and (ii) audification. This section focuses on the latter.

Gregory Kramer describes in his book *Auditory Display* that "audification" refers to the direct playback of data samples.[138] Later, he refines this definition by stating that “audification is the direct translation of a data waveform into sound.”[139] The purpose of audification, as with all sonification methods, is to reveal aspects of the data that may not have been previously noticed through other modes of representation. This technique provides a direct alternative to visualization, as any abstract data series can be either visualized or sonified.

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[137] It is worth noting that musical scores can only represent music for which there is consensus on the interpretation of symbols used within them.

[138] Kramer, 1994, pp. xxvii.

[139] Walker & Kramer, 2004, pp.152.

Audification involves interpreting one-dimensional signals (or two-dimensional signal-like data sets) as variations in amplitude over time and playing them through a loudspeaker for auditory analysis. Since all data are ultimately conveyed via a loudspeaker, audification represents a continuous, analog interpretation of these data sets. Different types of data produce distinct sounds when audified. Consequently, the definition encompasses all data sets that can be listened to, including all sound recordings themselves. The types of data that can be used in audification are as follow:

3.1.1.1: Sound Recording Data

The first type of data suitable for audification are sound recordings, which are typically digitized as numerical sequences. In essence, every CD player includes an audification module in the form of a Digital-to-Analog (DA) converter, which transforms these numerical sequences into continuous audio signals. From a sonification perspective, simply listening to sound recordings may not seem particularly noteworthy. However, amplifying these recordings can uncover previously inaudible details, and manipulating the playback speed through time-compression or time-stretching can make them even more intriguing. For instance, ultrasonic signals, like bat calls, are inaudible to humans unless their frequency is altered (Refer to media files #3 & #4).[140] Thus, altering playback speed serves a more significant purpose than mere novelty, allowing audification to act as an acoustic microscope or telescope.

3.1.1.2: General Acoustical Data

Measurements in elastomechanics, which adhere to the same physical principles as acoustic waves, are a significant focus for audification. Vibrational data from mechanical waves are particularly accessible when listened to through audification. Whether it involves listening to a railroad rail, a mast, or a human abdomen, using sounding-boards, stethoscopes, or sonar, we are accustomed to interpreting mechanical waves acoustically. Although mechanical waves are

[140] Example #3: Bat calls (inaudible) The frequency of bat calls is beyond the range of human hearing, which spans from 20 Hz to 20 kHz. And Example #4: Bat call (audible) The initial sample has been lowered by three octaves, bringing it into the audible range.

always a combination of compressional and transverse waves, their characteristics are generally preserved when converted to a one-dimensional audio signal. Additionally, altering the playback speed typically has a minimal effect on the authenticity of the sound produced. This is especially true in Auditory Seismology, where seismograms are often audified with acceleration factors exceeding 2,000 (See Media File #5).[141]

3.1.1.3: Physical Data

Measurements of various physical processes beyond the mechanical realm can also be converted into sound. However, data such as electromagnetic waves generally do not possess acoustic qualities that we commonly encounter. The varying speeds of wave propagation, along with differing dimensions of refraction and reflection effects, create a soundscape that is novel to human perception. Consequently, caution is necessary when interpreting these sounds; for instance, EEG data from multiple electrodes placed around the head should not be directly compared to a similar setup of microphones in a room (See Media File #6).[142]

3.1.1.4: Abstract Data

The challenge of interpreting audified abstract data, particularly those unrelated to physical systems, can exacerbate when individuals lack acoustic familiarity. Instances of such non-physical data include stock market information or the sounds produced by a fax machine (see media file #7) or a computer modem during telephone communication (see media file #8).[143] Unlike conventional waveforms governed by the wave equation, not all wave-like patterns in abstract data adhere to such principles, thereby requiring users more time to acclimate to the audified signals. Nonetheless, arranging non-acoustic and abstract data in a chronological sequence facilitates their audification process.

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[141] Dombois ,F., 2002.| Example #5: Earthquake, This sample from the website sonifyer.org features an audification of the Tōhoku earthquake that struck Japan in March 2011. Seismic waves resemble audio waves but move at a significantly slower pace. By accelerating the playback, these seismic movements become audible.

[142] Example #6: Electroencephalogram (EEG) Data, Extract sourced from sonifyer.org. Sonification of Alpha-wave recordings.

[143] Example #7: Early Fax Machine (Audio representation of a early fax machine in operation.) & Example #8: Early Computer Modem (Audio depicting the sound emitted by a computer modem from the 1990s.)

3.1.2: Audification in the Art

Audification originates not only from scientific endeavors but also from the realm of arts. The earliest documented instance of audifying abstract data can be traced to Rainer Maria Rilke, a German poet, in 1919. Rilke's essay "Ur-Geräusch" (Primal Sound)[144] contemplates the form of a skull's coronal suture,[145] envisioning its shape translated into an auditory experience.

> *What the coronal suture yields upon replay is a primal sound without a name, a music without notation, a sound even more strange than any incantation for the dead for which the skull could have been used.*[146]

A significant text authored by László Moholy-Nagy, in collaboration with Piet Mondrian in 1923, discusses the concept of creating New Music through the direct etching of sound curves onto records.[147] This process essentially involves turning graphical lines into auditory representations, predating the invention of computers.[148]

In response to the renowned "Farbe-Ton-Kongreß" in Hamburg in 1932,[149] Oskar Fischinger embarked on an exploration of painting decorative patterns directly onto the soundtrack of a film (refer to Figure 5).[150] This innovative method yielded novel synthetic sounds reminiscent of those generated by electric synthesizers, garnering significant attention from the press across Europe, the United States, and even Japan.[151]

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[144] See Rilke, 1919. & Huss, 2023.

[145] As per Britannica (2020), the coronal suture is described as a curved line delineating the frontal bone from the two parietal bones at the sides of the skull..

[146] Kittler 1999, pp. 44–45.

[147] Moholy-Nagy, László, 1923.

[148] A concept reminiscent of etching a disc was proposed when soundtracks were introduced to films during the 1920s.

[149] The initial two conferences on the correlation between color and tone, convened in Hamburg, Germany, in 1927 and 1930 respectively, exerted significant influence on the evolution of synesthetic art.

[150] Originally printed in the Deutsche Allgemeine Zeitung on July 8, 1932; see Moritz (2004, pp. 42-44) for further details

[151] Fischinger encountered obstacles in securing funding for additional research, resulting in the release of only a limited number of recordings. Despite this setback, these recordings garnered praise from notable figures such as John Cage and Edgard Varèse.

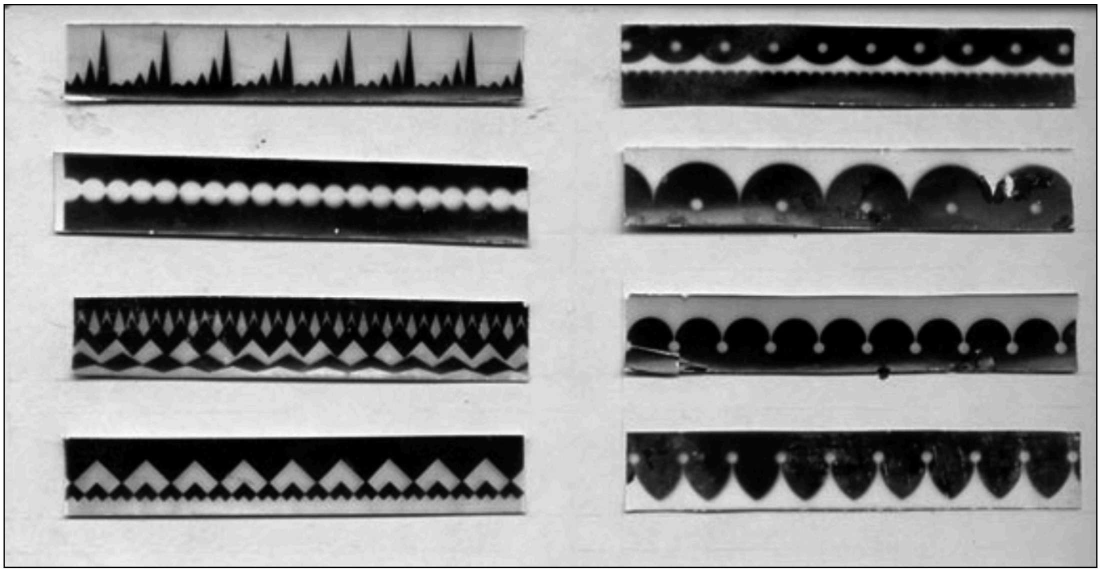

Figure 5: *Oskar Fischinger's studies of sounding ornaments.*

A different lineage can be traced through composers of New Music who employed novel technology in their compositions. For instance, in 1922, Darius Milhaud embarked on experiments involving "vocal transformation by phonograph speed change"[152] in Paris, a pursuit he continued for the subsequent five years. The 1920s also witnessed the emergence of various early electronic instruments, such as the Theremin, the Ondes Martenot, and the Trautonium, designed to replicate microtonal sounds (see media files #9 & #10 & #11).[153] The inception of electronic music can also be viewed as a narrative of audification, as all electronic instruments utilize electric processes translated into audible sound through speakers.

In 1948, Pierre Schaeffer introduced the concept of "musique concrète," marking a significant departure in music composition by incorporating recorded materials and sound samples. This innovation spurred various techniques for manipulating and refining acoustic elements, including time axis manipulation, transpositions, reverse playback, filtering, initially employing audio tape

[152] Russcol, 1972, pp. 68.

[153] Example #9: Theremin; Leon Theremin performing on his own invention in a television segment (with piano accompaniment) & Example #10: The Ondes Martenot (Jean Laurendeau performs Olivier Messien's "Turangalîla-Symphonie" on an Ondes Martenot instrument.) & Example: #11: The Trautonium, an early electronic instrument, was performed by the German composer Oskar Sala on Dutch television, accompanied by piano.

and record players, and later transitioning to computer-based methods. Additionally, artists began exploring previously unheard soundscapes, as exemplified by Jean Cocteau's fascination with ultrasounds, envisioning a vivid world of vocalizing fish populating the seas with their cacophony.[154] Artistic projects like Wolfgang Müller's "BAT" LP record from 1989, featuring down-pitched ultrasounds, garnered attention in the art community for their ability to unveil a realm beyond the audible, effectively rendering the inaudible perceptible (Refer to Media File #12).[155]

This section refrains from delving deeper into the extensive narrative of additional developments in data processing with auditory outcomes, specifically, the evolution of electronic music, as it veers too far from the central focus on audification and, therefore, opts to defer to the available body of literature on this topic.

3.1.2.1: Artistic Examples using Audification

Interest in generating novel auditory experiences, particularly within the realm of computer music, has prompted numerous musicians to explore the audification of diverse datasets. However, this section focuses solely on a select few instances of deliberate audification in recent years, where the resulting sounds have been utilized with minimal aesthetic alterations. Omitted from consideration is the extensive collection of works that directly convert mechanical waves into sound waves without intermediary adjustments.

A notable undertaking is "According to Scripture," a project by Paul DeMarini in 2002, which brought to life a collection of visual waveform diagrams dating back to the 19th century. These diagrams, created without the use of a phonograph, were directly drawn on paper.[156] Included in

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[154] Cocteau, J.“Die Welt des Tons ist durch die noch unbekannte Welt des Ultraschalls bereichert worden. Wir werden erfahren, daß die Fische schreien, daß die Meere von Lärm erfüllt sind, und wir werden wissen, daß die Leere bevölkert ist von realistischen Geistern, in deren Augen wir ebenfalls Geister sind.”, 1983, pp. 36f .

[155] Example #12: BAT (Müller, Wolfgang: Track 1 from the album “BAT” released in 1989)

[156] See Ouzounian, Gascia, 2010, pp. 10-21.

this project is the digitization and restoration of E.W. Scripture's renowned annotations from 1853–1890, enabling listeners to access the earliest recorded sounds ever documented.

Christina Kubisch introduced her renowned artwork, "Electrical Walks" (media file #13),[157] in 2004. Participants are equipped with headphones that convert electromagnetic induction from the environment into audible signals, accompanied by a city map outlining a recommended route.[158] This innovative use of technology creates an expansive auditory experience, reshaping the urban landscape for the listener.[159]

In 2004, the Australian collective Radioqualia presented their work "Radio Astronomy"[160] at the Ars Electronica Festival in Linz, allowing attendees to listen to real-time recordings of Very Low Frequency (VLF) signals.[161] This collaborative project involved partnerships with the Windward Community College Radio Observatory in Hawaii, USA, NASA's Radio Jove network, the Ventspils International Radio Astronomy Centre in Latvia, and the cultural center RIXC from Riga, Latvia.

Florian Dombois presented a series of sound installations featuring seismological data under the theme of "art as research" at Cologne Gallery Haferkamp in 2003 and 2006, as well as at Gallery Gelbe MUSIK in Berlin in 2009, among other venues.[162] One of these installations, titled "Circum Pacific" (Media File #14),[163] allowed audiences to listen to recordings from five seismic stations tracking seismic events around the Pacific plate.[164]

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[157] Example #13: "Electronic Walks" (2003) by Kubisch, Christina, from the sound installation.

[158] See Cox, Christoph, 2006.

[159] See http://www.cabinetmagazine.org/issues/21/kubisch.php (accessed May 27, 2024)

[160] See https://www.fondation-langlois.org/html/e/page.php?NumPage=383 (accessed May 27, 2024)

[161] VLF, which stands for Very Low Frequency, pertains to a specific range of radio frequencies commonly found within the spectrum of 3 to 30 kilohertz (kHz), particularly relevant in the realms of radio astronomy and radio communications.

[162] See https://www.mvt-journal.com/florian-dombois (accessed May 30, 2024)

[163] Example #14: Dombois presents "Circum Pacific 5.1," featuring a brief segment lasting three minutes, showcasing two audio channels extracted from the larger sound installation. One channel represents Antarctica, while the other depicts Papua New Guinea.

[164] See Kunsthalle Bern, 2010.

In the subsequent year, 2005, at the Ars Electronica event, Jens Brand, a German artist, presented "G-Player" (Media File #15).[165] This artwork features a conceptualization by Brand wherein he utilizes a topographical representation of the Earth and envisions satellites functioning akin to the needle of a phonograph, enabling direct auditory exploration of a topographical cross-section along their flight path.[166]

3.2: Parameter Mapping Sonification

3.2.1: Introduction

Parameter Mapping Sonification (PMSon) entails linking information to auditory parameters to visualize data. Given the multidimensional nature of sound, PMSon is inherently suitable for representing multivariate data. The natural acoustical output resulting from material, electrical, or chemical interactions, or their conversion to electroacoustic signals, can serve as a direct method of data interpretation. For instance, the sound produced by a tea kettle as water approaches boiling exemplifies this concept. However, unlike the audible cues from boiling water, the desired output signal for monitoring may fall below perceptual thresholds or exceed the limits of human hearing. Additionally, the direct acoustic signal often integrates multiple factors, necessitating the selective attention to certain attributes while disregarding others.

The whistle of our tea kettle, arguably, produces a significant amount of noise to convey a simple binary signal, indicating the need to remove the kettle from the stove and pour the water. A simpler, though potentially less charming, auditory cue could be achieved by monitoring the temperature of the water in the kettle using a thermometer and translating the numeric data into sound parameters. For instance, a straightforward mapping could associate temperature with

[165] Example #15: “G-Player”, 2004. Brand, Jens: Acoustic segment extracted from the multimedia installation.

[166] Kiefer, 2010, pp. 342f. Also see https://www.jensbrand.com/gplayer_images.html (accessed May 27, 2024)

frequency, pitch, or a more direct auditory cue. Rather than only hearing when the desired temperature is reached, one might prefer to listen to the continuous progression of the water temperature, or to hear specific temperatures at different stages of the heating process, as exemplified in the audio files illustrating the five traditional stages of Chinese tea preparation (See media files #16 & #17 & #18).[167]

3.2.2: Mapping Problem: Case Study

Mapping in sonification presents both opportunities and challenges. The extensive array of mapping decisions offers ample possibilities for creating suitable auditory representations tailored to specific purposes. However, the diverse range of mapping options also presents difficulties in maintaining consistency and ensuring comprehensibility. While associating temperature with frequency or pitch provides an intuitive and effective method for monitoring tea preparation, it is essential to acknowledge the loss of information when substituting the direct auditory output of the kettle's whistle with this simplified mapping. The whistle's sound holds a universally understood significance for many individuals.

For numerous individuals, the sound evokes positive emotions. Moreover, there exists an element of anticipation and musicality in the progression from noise characterized by fluctuating and irregular frequencies to a more consistent frequency.[168] Consequently, while PMSon may provide accuracy and effectiveness in presentation, it is crucial to assess its intuitive nature, as

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[167] Example #16 involves the use of sound to represent the moment of reaching a particular data point in a time-series, demonstrated by a recorded sound playing when water in a teakettle boils.
In Example #17, both the progression of a time-series and the reaching of a specific data point are sonified. This is illustrated by the continuous change in water temperature being accompanied by a distinct sound when the boiling point is reached during the boiling process in a teakettle.
Example #18 explores sonifying individual data points within a sequence alongside the overall process. It demonstrates the continuous increase in water temperature with five specific data points, each mapped to a stage of heating water in traditional Chinese tea preparation, as simulated here

[168] The recognition that idiophonic acoustic output frequently embodies music rich in variations and intricacies, brimming with inherent information, is the focal point of the nascent discipline known as auditory augmentation (Refer to Bovermann et al., 2010, and Grond et al., 2011).

well as aesthetic and emotional considerations which may be preferred and even essential in auditory displays. Subsequent sections will delve into these aspects.

Sound example #17 exhibits the real-time tracking of temperature fluctuations in a tea kettle, representing temperature changes directly as changes in frequency (e.g., 100°F corresponds to 100 Hz) at a relatively high sampling rate. This method offers both numerical and temporal accuracy necessary for the intended purpose. However, unlike in the preceding sound example #16, where the auditory display is designed to produce sound only at the boiling point (thus, yielding an intuitive and effective outcome with any mapped sound), this presentation lacks a clear contextual and goal-oriented representation. A straightforward solution could involve incorporating a reference tone denoting the boiling point, which would accompany the sonification, akin to the approach in media file #19.[169] This reference tone serves as a comparable concept to a gridline on a graph. Without this reference, the listener would need to possess absolute pitch and prior knowledge that 212°F corresponds to the boiling point of water.[170] Implicit within these instances is the understanding that the sound parameters utilized for mapping may be either physical (e.g., frequency) or psychophysical (such as pitch).[171]

Designing an effective PMSon often necessitates finding a balance between intuitive, enjoyable, and precise display characteristics. For instance, in the sound example #18, temperature readings are taken at specific time intervals and translated into pitch variations. Unlike the auditory representation resembling a 'line graph' in sound example #17, this approach mirrors a scatter plot. Similar to visual graphs, each approach carries its own advantages and limitations. Utilizing discrete data polling through sound, interspersed with moments of silence, results in a display that strikes a balance between being noticeable without becoming overly repetitive. This

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[169] Example #19 involves the inclusion of a reference tone, mirroring Example #18 but with the continuous presence of the boiling point. The gradual decrease in frequency beating leading to a harmonious unison elucidates and foreshadows the eventual culmination point.

[170] In fact, since 212 F, or better 212 Hz, falls between G#3 and A3, even absolute pitch might not be sufficient.

[171] As elaborated later, mappings can also encompass intricacies in temporal and/or frequency domains, such as timbre, chords, melodic sequences, or rhythmic patterns.

technique blends elements of artistry and scientific precision. In sound example #20,[172] the temperature of tea water is converted into quantized frequencies, aligning with a pentatonic scale featuring pitch classes [C, D, E, G, and A] on the musical scale.

The lowest audible pitch corresponds to C2, while 212°F is associated with C5, with all other pitches adjusted to fit within this range. Despite regular temperature sampling, the number of sonified data points varies based on temperature, with higher temperatures resulting in more frequent and higher-pitched sounds until reaching the boiling point, at which pitch repetition occurs every 200 milliseconds. The volume is set to a level that neither blends into the background noise nor exceeds the masking threshold significantly, utilizing a recognizable timbre with a relatively high degree of harmonic richness, resulting in a generally pleasant, subtle, and effective display. These mapping decisions, although intuitive, are somewhat arbitrary and are compounded by the numerous variable parameters inherent in audio, not to mention the addition of further dimensions for display, highlighting both the strengths and challenges in implementing effective PMSon.

Apart from determining specific intervals for representing data, there exists a vast array of sound parameters and practically boundless scaling techniques to select from. Therefore, achieving the ideal mapping involves considering several factors, even in this basic scenario. These include identifying the task-relevant aspects of the data for auditory representation, determining the granularity of the display (i.e., how detailed the auditory representation should be), choosing suitable sound dimensions and parameters, and deciding on the appropriate scaling method for the chosen parameter.

It's crucial to acknowledge that the development of Western music notation has been a gradual process spanning centuries, driven by the need to accurately capture the nuances of musical elements such as texture, pitch, timbre, and rhythm. Thus, music notation serves as a translation

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[172] Example #20: Mapping tea water temperature to quantized frequencies corresponding to a pentatonic scale with pitch classes [C, D, E, G, and A] on the musical scale is illustrated in sound example S15.5. The lowest pitch produced is C2, while 212°F corresponds to C5, with all other pitches adjusted to fit within this range.

from visual symbols into the auditory dimensions of pitch, volume, duration, and timbre, while time progresses according to an independent tempo. The unique challenge in sonification lies in creating notations that are both functional and practical, akin to those used in music, while also effectively representing the more abstract signal domain. It's essential to maintain focus on the primary goal of mapping and representing data rather than musical concepts.

3.2.3: Artistic Applications of PMSon

The utilization of PMSon in artistic expression has served as a catalyst for the creation of numerous musical compositions. These compositions often draw inspiration from time-based datasets, including solar activity, tides, and meteorological records.[173]

Throughout history, composers have drawn inspiration from geometric relationships and mathematical procedures. Notable instances include the incorporation of Brunelleschi's Basilica di Santa Maria del Fiore's architectural proportions into Dufay's *Nuper Rosarum Flores* (1436), as well as Xenakis' utilization of statistical and stochastic processes to translate into sound in compositions like *Metastasis* (1965) and others.[174]

An alternative method in the realm of Parameter Mapping Sonification (PMSon) for artistic purposes involves associating geographic coordinates with auditory elements. For instance, Larry Austin's composition *Canadian Coastlines: Canonic Fractals for Musicians and Computer Band* (1981) utilized the contours of Canadian coastlines to generate compositional data. Another contemporary illustration of PMSon is found in Jonathan Berger's *Jiyeh* (2008),[175] which translates the patterns of oil dispersion resulting from a catastrophic mediterranean sea oil spill into auditory form. By utilizing a sequence of satellite images, the electroacoustic rendition of

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[173] see for instance Flood Tide (2008) and Hour Angle (2008) by Eacott: http://www.informal.org (accessed May 30, 2024)

[174] To explore a compilation of "historic" sonifications and mappings, refer to: http://locusonus.org/nmsat (accessed May 27, 2024)

[175] [...] which comprises two renditions: one tailored for eight-channel computer-generated audio, and another for a combination of violin, percussion, cimbalom, and string orchestra. Refer to http://ccrma.stanford.edu/~brg/jiyeh/ (accessed May 28, 2024)

Jiyeh sonifies and scales the temporal and spatial spread of the oil, conveying the magnitude of the environmental incident.

PMSon has been applied in sonification of biofeedback. Alvin Lucier's composition *Music for Solo Performer* (1965) transforms the composer's brain activity captured via electro-encephalogram scalp electrodes into resonating percussion sounds, although this method, while artistically effective, provides limited informative value. Image-based sonifications for artistic expression have been achieved using the software SONART.[176] Tanka has produced several pieces that translate images into auditory experiences, one notable example being *Bondage* (2004).[177] which maps images to spectral sound features. A similar technique is employed in Grond's *Along the Line* (2008),[178] which investigates the use of space-filling curves for spectral mapping.

Several sound installations incorporate environmental data, such as Berger's *Echos of Light and Time* (2000), which monitored sunlight intensity and temperature over 18 months in collaboration with sculptor Dale Chihuly.[179] Halbig's *Antarktika* (2006)[180] translates ice-core data representing Earth's climatic evolution into a string quartet score. Chafe's *Tomato Quintet* (2007, 2011)[181] transforms the ripening process of tomatoes into sound. This process involved mapping carbon dioxide, temperature, and light readings from sensors in each vat to synthesis and processing parameters. Following this, the resulting sonification was time-scaled to various durations.

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176 Ben-Tal, O., et al. 2002.

177 Tanaka, 2012.

178 See http://www.grond.at/index.htm?html/projects/along_the_line/along_the_line.htm&html/submenues/submenu_projects.htm (accessed May 27, 2024)

179 See https://ccrma.stanford.edu/~brg/echoes.html (accessed May 27, 2024)

180 See http://www.antarktika.at (accessed May 26, 2024)

181 See https://ccrma.stanford.edu/~cc/shtml/2007tomatoQuintet.shtml (accessed May 28, 2024)

3.3: Model-Based Sonification

3.3.1: Introduction

Model-Based Sonification stands apart from Audification and Parameter Mapping Sonification in its conceptual approach. Unlike the latter techniques, MBS focuses on examining how user actions generate acoustic responses, providing a framework for translating these insights into data sonification. This method necessitates the development of systematic processes involving data, capable of evolving over time to produce an auditory signal. A sonification model serves as the blueprint for creating such a "virtual sound-capable system"[182] and guides interactions with it. These models typically remain silent until activated by user input, dynamically adjusting their behavior in response. The resulting sonification directly mirrors the temporal evolution of the model.

3.3.2: Model-Based Sonification: a Definition

According to Hermann, Model-Based Sonification (MBS) encompasses various concrete sonification techniques that employ dynamic models to mathematically describe a system's evolution over time. These techniques parameterize and configure the models with available data during initialization and provide interaction/excitation modes for users to actively elicit sonic responses. These responses systematically depend on the temporal evolution model.[183]

Model-Based Sonification (MBS) serves as a comprehensive framework for delineating, conceptualizing, and executing task-specific sonification techniques. Within this framework, a specific instantiation is referred to as a sonification model. While MBS draws inspiration from principles of physics, designers retain the flexibility to deviate from these principles and even devise non-physical dynamic models. A systematic approach to crafting sonification models

[182] Hermann, 2011, pp. 399.

[183] Hermann and Ritter, 1999.

within the MBS framework involves sequentially defining six key components: setup, dynamics, excitation, initial state, link variables, and listener characteristics, each of which will be elaborated upon in the following sections. (See Figure 6)

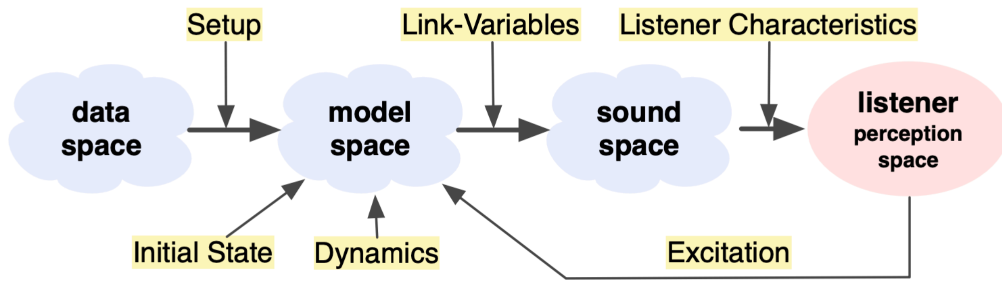

Figure 6: *The progression from 'data space' via 'model space' to sound space and to the 'perception space' of the listener.*

These procedures are demonstrated through the utilization of a straightforward MBS sonification model known as data sonograms. Essentially, the data sonogram sonification model enables users to initiate a shock wave within the data space, which gradually expands spherically. Consequently, the wave-front triggers mass-spring systems connected to positions determined by the coordinates of each data point. Through this sonification technique, users can perceive the spatial arrangement of data and observe how data density varies concerning the center of shock wave excitation.[184]

Model-Based Sonification (MBS) serves as an intermediary between data and sound through the utilization of a dynamic model. Unlike audification where data directly dictates the sound signal or parameter mapping sonification where data determines sound features, MBS establishes a 'dynamic' model architecture influenced by the data, subsequently generating sound. This

184 Although the data sonogram sonification model proves beneficial for an MBS tutorial, it's crucial to note that it represents just one specific example. Other models may exhibit significant structural variations, including "Tangible Data Scanning," "Principal Curve Sonification," "Data Crystallization Sonification," "Particle Trajectory Sonification Model," and "Growing Neural Gas Sonification Model."

approach introduces the model space between the data and sound realms, as illustrated in Figure 6. Sound examples #21a, #21b, & #21c provide typical data sonograms for clustered datasets.[185]

In essence, the model-based approach to sonification contrasts with event-based techniques. Rather than directly mapping data parameters to sound, this approach entails constructing a virtual model. This virtual model generates acoustic responses to user interactions based on the underlying data. Essentially functioning as a virtual instrument or entity, the model enables users to engage interactively. The resulting sounds mirror the data-driven responses to user input. By engaging with this virtual model, users extract insights into the data's structure through its auditory feedback. Model-based sonification heavily relies on user interaction to shape the auditory output, typically handling extensive datasets and intricate data points. Examples include Shoogle, which converts text messages into sound by shaking,[186] the Local Heat exploration model,[187] and Data bubbles,[188] Markov-chain Monte Carlo sonification,[189] data solids,[190] Multitouch GNGS,[191] and scatter plot exploration for visually impaired

Shoogle *is a novel, intuitive interface for sensing data within a mobile device, such as presence and properties of text messages or remaining resources*

[185] Examples #21 (a, b, c) present sonograms derived from the Iris dataset, comprising 150 data points, with each point representing a distinct Iris flower characterized by four geometric measurements. These data points cluster into three distinct groups, each associated with a biological classification. Interestingly, each type of Iris emits a distinct sound. By examining the dataset through auditory representations, it becomes evident that the different Iris types form cohesive clusters.

[186] Williamson, J., Murray-Smith, R., & Hughes, S., 2007.

[187] Bovermann, T., Hermann, T., & Ritter. H. (2005), also see https://pub.uni-bielefeld.de/record/2699962

[188] Milczynski, M., Hermann., T., Bovermann, T., & H. Ritter. (2006), also see https://pub.uni-bielefeld.de/record/2700564

[189] Hermann, Hansen, & Ritter, 2001.

[190] Hermann, Krause, & Ritter, 2002, pp. 82-86

[191] Kolbe, Tünnermann, & Hermann, 2010. Also see Tünnermann et al., 2009.

individuals using active tangible objects.[192] (See media files #22 & #23)[193]

3.4: Other Techniques

3.4.1: Auditory Icons and Earcons

Auditory icons seek to establish an "intuitive connection" between the metaphorical environments of computer programs by audibly depicting objects and events within the applications, employing sounds that are recognizable to users from their daily experiences.[194] (See media files # 24 & #25 & #26)[195]

Auditory icons necessitate a pre-existing correlation between the sound and its significance.[196] However, instances exist where certain objects or occurrences lack a natural auditory counterpart, thus necessitating the provision of an aural metaphor through Earcons. These are described as non-verbal audio cues utilized in human-computer interfaces to convey information to users. Earcons serve as the auditory equivalent of icons[197] as they do not presuppose prior familiarity with the metaphor; rather, the user must learn the association between the information and the sound. Brewster further elaborated on this concept, defining Earcons as abstract,

[192] Riedenklau, Hermann, & Ritter, 2010, pp. 1-7

[193] Example #22: Physical Data Exploration This video demonstrates Physical Data Exploration, an engagement with data sonograms facilitated by an interactive tool held by the data analyst. It showcases the exploration of data space using a grouped dataset (specifically, the Iris dataset mentioned in Example #26)
Example #23 demonstrates the sonification of the growth process in Growing Neural Gas (GNG), featuring a video illustrating the growth of a GNG model applied to a 2D spiral dataset

[194] Brazil and Fernström, 2011, pp. 326

[195] Instances include Water splashing (Example #24), Walking or footsteps on tarmac (Example #25), and Closing a door (Example #26).

[196] McGookin and Brewster, 2011, pp. 339.

[197] Blattner et al., 1989, p. 13

synthetic tones that can be arranged in structured combinations to communicate auditory messages.[198] (see media files #27 & #28)[199]

3.4.2: Additional Classification of Sonification Techniques

Several authors delineate the field of sonification in varying manners, though the classifications generally echo the organization proposed previously. For instance, Barrass outlines distinct techniques, including Sinification, MIDIfication, Musicification, Vocalization, Iconification, and Stream-based approaches. Sinification involves mapping data to sine-tones, while MIDIfication employs MIDI notes for this purpose. Musicification utilizes musical scales and chords, and Vocalization employs synthesized vowel sounds. Iconification utilizes "metaphorical connotations," and Stream-based sonification employs granular synthesis.[200] Essentially, these techniques collectively constitute Parameter Mapping Sonification (PMSon), differing primarily in their sound source. Depending on its application and design, Iconification could also be categorized as an auditory icons technique.

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[198] Brewster 1994.

[199] Example #27: An Earcon undergoing transformation depicting a theme park attraction. (This Earcon signifies a static theme park ride characterized by high cost and intensity.)
Example #28: An Earcon undergoing transformation illustrating a theme park attraction. (This Earcon signifies a static theme park ride with moderate cost and intensity. Note the variations in register and rhythm compared to example #4, while maintaining the same timbre representing the ride type.) Both examples are provided by McGookin (2004).

[200] See Barrass, 2012, pp. 180; & Barrass, 2003.

Chapter 4: Sonification in Artistic Context

4.1: Sonification and Aesthetic Consideration

The concept of creating music from sources beyond traditional musical elements predates Beethoven; for example, the Greeks utilized geometric ratios, and Mozart employed dice. In the 1930s, Joseph Schillinger[201] introduced a mathematical approach to music composition, which has been described as "a sort of computer music before the computer".[202] With the advent of electroacoustic technologies, Iannis Xenakis began composing music based on statistics and stochastic processes (see media file #29).[203] Nowadays, computer music is generated using fractal equations, cellular automata, neural networks, expert systems, and other rule-based systems, algorithms, and simulations.[204] Additionally, music is being composed using DNA sequences, financial indices, internet traffic, Flickr images, Facebook connections, Twitter messages, and virtually any digital data.

Typically, a composer focuses on the musical experience rather than revealing the compositional elements. However, making the data or algorithm explicit prompts the question of whether certain aspects of the phenomenon can be understood by listening to the composition. "When the intention of the composer shifts to the revelation of the phenomenon, the work crosses into the realm of sonification."[205] Historically, sonification has predominantly been the domain of scientists, engineers, and technologists who use synthetic sounds for observation and investigation. These experiments have often faced criticism for being unpleasant to hear and difficult to interpret, with further critiques suggesting that the process of creating sonifications is often more insightful than the resulting sounds.

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[201] Schillinger, 1941.

[202] Degazio, J. Bruno.

[203] Xenakis, 1991. Example #29: *Concret PH* by Xenakis, a piece of music created utilizing statistical and stochastic methods

[204] Roads, 1998.

[205] Barrass & Vickers, 2011.

This section discusses a design-centered approach to address functionality and aesthetics in sonification, that integrates both scientific and artistic methodologies. The section commences with an exploration of design methodologies and practices in sonification, followed by an argument for a pragmatic information aesthetic that differentiates sonification from computer music. Subsequently, it discusses aesthetic design principles and metrics for sonification. Finally, it posits that this design-oriented approach could position sonification as a widely accessible medium for conveying and appreciating non-verbal information through sound.

4.1.1: Background: Sound Conveying Information - From Program Music to Auditory Displays

The question of whether music can convey meaning beyond its own form has been a topic of debate since the 18th century and remains unresolved. Formalists maintain that music, as the most abstract of the arts, is confined to its own elements of melody, harmony, dissonance, tension, and resolution. In contrast, Beethoven's sixth symphony (the Pastoral) is frequently highlighted as an instance of program music, with a narrative suggested by the titles of its five movements and the music itself (see media file #30).[206] The symphony's depiction of peasants dancing under a tree reaches a peak with a vivid orchestral thunderstorm, foreshadowing the use of sound in film. Beethoven's margin note on the manuscript, “Mehr Ausdruck der Empfindung als Malerei,”[207] signifies the emergence of a type of program music that transcends mere imitation of sounds to create an imagined drama or represent a poetic idea.[208]

Subsequently, the introduction of the optical movie soundtrack enabled Foley recordings like footsteps to synchronize with on-screen events. This technological advancement prompted film sound designers to innovate, expanding the use of sound effects to depict off-screen actions,

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[206] Example #30: Beethoven's Pastoral Symphony, 4th Movement. This piece exemplifies program music, where the narrative is expressed through the titles of its five movements. The story, which depicts peasants dancing beneath a tree, culminates in a vigorous orchestral portrayal of a thunderstorm, foreshadowing the sound design techniques used in modern cinema.

[207] In English; “More expressive of emotions than a painting”.

[208] Consider Bedřich Smetana’s composition "The Moldau" as an example. This piece sonically illustrates the flow of the Vltava River, also called the Moldau. Initially, it captures the river’s journey from its origins in the Bohemian Forest mountains. It then tracks the river as it meanders through the countryside of Czechoslovakia, and ultimately, it portrays the river’s course as it reaches Prague (Straebel, 2010, p. 287)

facilitate cuts and scene changes, signify flashbacks, and direct audience focus. This led to the development of a film sound theory; Chion, building on Pierre Schaeffer's earlier work, proposed three listening modes: causal (focused on the sound source), semantic (concerned with sound meaning), and reduced (attuned to sound properties).[209] Furthermore, the advent of magnetic audio tape marked a significant milestone in musical innovation, enabling techniques such as musique concrète, cutup, reversal, and looping. However, it wasn't just musicians who explored these new capabilities. Seismologists, for instance, accelerated recordings of earth tremors to detect sub-sonic events, which allowed them to differentiate between earthquakes and underground nuclear tests.[210]

The development of analogue synthesizers further enhanced control over sound through knobs and sliders. Patterson utilized these synthesizers to create sounds replicating those in an aircraft cockpit, analyzing the effects of amplitude, frequency, tempo, and pulse patterns. He proposed guidelines for cockpit warning and alarm sounds, recommending onset and offset times of 30ms or more, limiting sound duration to 100ms, using patterns with at least five pulses, associating pulse rate with urgency, and restricting the vocabulary of symbolic sounds to seven.[211] Bly explored the perception of multivariate data through sound by mapping six-dimensional data onto six characteristics of a synthesized tone (pitch, volume, duration, waveshape, attack, and overtones). Her participants were able to classify the data from the auditory display as effectively as from a visual representation.[212] In 1992, Gregory Kramer brought together these pioneering researchers by establishing the International Conference for Auditory Display (ICAD).[213]

At the third ICAD conference held at Xerox PARC in 1996, a session focused on Design Issues in Auditory Displays. During this session, Tkaczevski[214] provided an overview addressing the

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[209] Chion, 1994.

[210] Hayward, 1994.

[211] Patterson, 1982.

[212] Bly, 1982.

[213] See http://www.icad.org (accessed May 29, 2024)

[214] Tkaczevski, 1996.

aesthetic, technical, and musical aspects of commercial sound design, while Back[215] introduced a sound design theory centred on micro-narratives. Walker and Kramer[216] shared results from an experiment where participants associated an increase in tone frequency with a rise in temperature, but a reduction in size. Another study revealed that sighted participants perceived an increase in frequency as signifying more money, whereas visually impaired participants interpreted it as indicating less money.[217]

4.1.2: Aesthetic Appreciation: Sonification Concerts

In their 2002 call for art submissions for the ICAD conference in Japan, Rodney Berry and Noatoshi Osaka emphasized the necessity of giving more attention to the aesthetic dimensions of sonification, highlighting its critical role in the meaning-making process. They noted, "In this year's ICAD we have included an art section in the hope that future ICADs might continue to explore some of the arguably less utilitarian aesthetic implications of auditory display." Due to budget and space constraints, they were only able to host one installation, which was *Acoustic Acclimation* by Singapore-based artists and composers Lulu Ong and Damien Lock, who work under the name Coscilia. This work does not merely provide an "aesthetically pleasing sonification of data-sets," but rather it examines the relationship between sound and meaning and how they combine to create a sense of place. The aim is that exposure to such works in future ICAD events might encourage attendees to think more deeply about the crucial mapping stage of auditory display and the interaction between data, information, and meaning, which is of interest to both scientists and artists.[218] moreover, during the conference, Bob Sturm revealed the launch

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[215] Back, 1996.

[216] Walker & Kramer, 1996.

[217] They proposed that this might be due to individuals in the visually impaired group utilizing a physical metaphor to interpret the sounds (see Walker & Lane, 2001).

[218] Berry & Osaka, 2002.

of a musical album featuring sonifications of spectral data from ocean buoys, titled "Music from the Ocean" (See media file #31).[219]

During ICAD 2003 in Boston, Marty Quinn introduced the idea of sonification as a potential musical experience, presenting a CD titled *For those who died*,[220] which featured sonifications created from data related to the September 2001 World Trade Centre attack. Barra et al.[221] delved into methods for mitigating listening fatigue by crafting sonifications with a "musical structure devoid of typical and traditional musical motifs," drawing inspiration from avant-garde composers such as Luigi Russolo (1885–1947), Pierre Schaeffer's musique concrète, Edgard Varèse's *Poème Electronique* (1958), and John Cage's aleatoric compositions like *Music of Changes*.[222] Additionally, The artistic possibilities of sonification as a medium have been explored by sound artists such as Andrea Polli, who utilized sonification techniques prominently in a public sound art exhibition addressing climate change (see media file #32):[223]

> My first geosonification collaboration with a scientist [Dr. Glenn Van Knowe] was the 2001 ‘‘Atmospherics/Weather Works’’ project, translating detailed data from of two historic storms that passed through the center of New York City. The two of us chose to experiment with a hurricane and a winter snowstorm and developed a series of 14-channel sonifications based on models of the storms at 5 different elevation levels. Responding to the cacophony of a large number of speakers simultaneously producing sound, I developed a reductive process for sonification by starting with a very noisy sound and using programmed filters to sculpt the sound into various shapes. I was inspired by wind har- monics, the way air moves between and through buildings and other man-made structures and is transformed into sound, and the unexpected kinds of sounds that can result from that process.[224]

The viability of sonification as a musical encounter underwent examination through the implementation of a concert featuring sonifications, which was open to the public and held at the

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[219] Sturm. *Music from the Ocean*, 2002. Example #31 is derived from Sturm’s compilation of sonifications representing spectral data collected from ocean buoys.

[220] Quinn, M., Quinn, W., & Hatcher, 2003.

[221] Barra et al., 2001.

[222] Barra, Cillo, De Santis, Petrillo, Negro, & Scarano, 2002, pp. 35.

[223] Polli, 2005. Example #32: Weather Works by Andrea Polli, who extensively employed sonification methods in a public sound art installation focused on climate change.

[224] Example #32: Andrea Polli utilized sonification methods extensively in a public sound art installation addressing climate change, titled Weather Works, Polli, 2012, pp. 299.

Sydney Opera House Studio.[225] The solicitation for entries for the "Listening to the Mind Listening" concert, showcasing EEG data, requested sonifications that were both “musically satisfying” and “data driven”[226] (refer to media file #33).[227] As outlined by Barrass and Vickers, numerous composers detailed how they successfully met these dual criteria in their submissions;

> Three used a notion of revelation or inherence, with a related idea that the data was musical in itself. One described the goal to be to “find naturally occurring rhythmic and musical structures in the data”. Another also invoked Nature: “Nature itself creates the structure and balance upon which aesthetics are based. It stands to reason that data captured from such activity is naturally aesthetic when interpreted properly”. At the same time, several identified the need to create or maintain musical “interest” and others noted that they selected or “highlighted” aspects that were more musically satisfying. Three recognized the duality of music and sonification as constraining, or even inherently conflicting. One wrote: “It is not to be expected that a sonification produced in a deterministic manner from the data will have any of the normal characteristics of a piece of music”. Some contributors emphasized information and perception rather than music, and only a small subset used both musical and perceptual discourses. Several identified with non-music sound practices, using terms such as audio, soundscape, or composition rather than music to describe the results.[228]

Alberto de Campo arranged a second concert of sonifications for ICAD 2006 in London titled "*Global Music, The World by Ear*," where eight sonifications of socio-economic data were premiered through an 8-speaker surround system at the Institute of Contemporary Arts.[229] This event marked a significant intersection of sonification and sound art. The momentum continued with ICAD 2009 being held concurrently with the RENEW symposium on sound art, featuring three nights of performances in Copenhagen.[230]

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225 Barrass, Whitelaw, and Bailes, 2006.

226 Barrass & Vickers, 2004. See http://www. icad.org/websiteV2.0/Conferences/ICAD2004/call.htm#concert (accessed May 27, 2024)

227 Example #33: Engaging with the auditory presentation "Untidy Mind" by Tim Barrass, as part of the Listening to the Mind Listening project, exemplifies one of the sonifications showcased during the concert. The invitation for submissions for the Listening to the Mind Listening event, featuring EEG data, specifically requested sonifications that combined musical appeal with a basis in data analysis.

228 Barrass and Vickers, 2011, pp. 150.

229 de Campo, 2006.

230 Barrass & Frauenberger, 2009.

The rising interest in the aesthetic aspects of research and the evolution of sonification as an artistic tool have blurred the boundaries between sonification and other practices. Hermann[231] aimed to clarify this distinction by redefining sonification within the realm of scientific methodology, introducing four criteria for identifying a work as sonification:

1. The sound representation reflects objective properties or relationships within the input data.
2. The transformation process is systematic, meaning there is a clear definition of how the data (and optional interactions) influence changes in sound.
3. Sonification is reproducible: when provided with the same data and identical interactions (or triggers), the resulting sound must remain structurally consistent.
4. The system is intentionally designed to accommodate different datasets while can also be repeated with the same dataset.[232]

Computer musicians and sonification researchers employ similar technologies, tools, and methodologies to systematically create sounds from data and algorithmic processes. However, what distinguishes sonification from other sonic practices is not merely its systematic approach but its functional intention. Sonification is a "rendering of data to sound with the purpose of allowing insight into the data and knowledge generation about the system from which the data is gathered."[233] Thus, sonification is characterized by a pragmatic information aesthetic that merges the functionality of information design with the artistic sensibilities of the sonic arts. Portraying sonification solely as a scientific endeavor risks exacerbating the divide between the scientific and artistic realms, as illustrated in C. P. Snow's[234] Two Cultures debate.[235]

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[231] Hermann, 2008.

[232] Hermann, 2008.

[233] Barrass & Vickers, 2011, pp. 152.

[234] C.P.Snow, 1959.

[235] For a detailed discussion on CP Snow's two-culture debate, refer to section "1.2.6: The Artist as Researcher; A Case Study"

4.1.2.1: Mapping in Sonification

According to Scaletti,[236] who provided one of the initial definitions of sonification, the concept comprises two elements: one related to the necessities of information and the other concerning how information is depicted.[237]

> [. . .] a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purpose of interpreting, understanding, or communicating relations in the domain under study.[238]

Barrass reevaluated Scaletti's characterization of sonification from a design angle, replacing 'interpretation' with the notion of 'usefulness'.[239] The resultant design-oriented definition posits sonification as the employment of nonverbal sounds to convey practical information, encompassing both utility and aesthetics, while circumventing the complex issues of accurate interpretation and objective communication. The concept of 'usefulness' permits diverse sonifications of identical data for various objectives and serves as a basis for assessment, iterative refinement, and theoretical development. This concept found resonance in the NSF Sonification Report of 1999, which also reverted to a more concise rendition of Scaletti's definition of sonification to establish the prevailing widely accepted definition.

> Sonification is the use of nonspeech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation.[240]

While this definition effectively describes parameter mapping sonifications, Hermann contended that it lacks accommodation for model-based sonification and other emerging techniques.[241]

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[236] Scaletti, 1994.

[237] Barrass, 1998.

[238] Scaletti, 1994, pp.224.

[239] Barrass, 1998.

[240] Kramer, Walker, Bonebright, Cook, Flowers, Miner, & Neuhoff, 1999.

[241] In model-based sonification, data serves as the foundation for creating sound models, with interactive tools enabling users to activate the model, resulting in the generation of sound that represents the data itself. In this approach, users essentially engage with the data through sound. According to Hermann, model-based sonification offers a unique avenue for data exploration, diverging from traditional mapping methods. He asserts that this technique integrates structural information directly into the sound signal, departing from a mere translation of data to sound.

4.1.3: Aesthetics: Senses and Perception

If sonification necessitates interdisciplinary collaboration, it prompts an inquiry into the significance of artistic practice and broader aesthetic considerations in sonification design. Sonification is considered as a visualization activity that employs sound to represent information from data.[242] Historically, the novelty of rendering data audibly may have led to the creation of sonifications, both past and present, that lack practicality, usability, or significance. Within the realm of graphical visualization, a discourse has emerged in recent years concerning the function's role and its interplay with data art. Lima[243] articulated objections to the notion of "data art as visualization" as follows: The critique varies slightly from person to person, but common themes include remarks such as "It's merely visualization for visualization's sake," "It's merely eye candy," and "They all appear alike."

Exploring the existing connections between graphical visualization and art is enlightening, particularly as the field of sonification faces similar challenges. The primary aim of visualization is to clarify the data being presented, enabling meaningful interpretation. Data becomes information when given significance; otherwise, it remains raw data. Although it's possible to extract meaning from data without employing representations (by analyzing raw data for patterns), both sonification and visualization focus on creating representations of data that aid in inference and meaning-making.

According to Lima, the work in question shouldn't be strictly classified as information visualization since it doesn't offer any valuable insights; instead, it merely serves as a spectacle. Its worth lies solely in its artistic qualities, lacking the essential usefulness typically expected from visualizations. Redström supports Lima's argument by highlighting a fundamental issue in

[242] The traditional understanding of visualization is captured by the definition provided by Quigley (2006, p. 320), which describes it as "the process of forming a mental image of some scene as described." Therefore, visualization refers to the cognitive process through which mental images and perceptions (referred to as visualizations) are constructed from the interpretation of external representations of data. These representations can take various forms, including visual, auditory, or haptic modalities. Data sets encompass collections of data, such as files or tables, while real-time data streams consist of ongoing sequences of data events, as might be encountered in applications for process monitoring.

[243] Lima, 2009.

design aesthetics, which revolves around how a design enables a computational entity to express its capabilities through its presentation and usage over time.[244] Because the "purpose of visualization is insight, not pictures"[245] so Redström emphasizes that the primary goal of visualization is insight, not merely creating images, shifting the focus of aesthetics towards the expressions and expressiveness of the subject matter.[246] This perspective prompts an examination of how the material formulates itself based on the underlying logic governing these expressions.

4.1.3.1: Aesthetic Turns

When Oscar Wilde famously declared that all art is essentially useless,[247] he wasn't disregarding its significance but rather emphasizing that the value of art lies in its intrinsic aesthetic qualities rather than its practical function; in essence, art exists for its own sake, just as tools serve a purpose. This assertion mirrors the enduring Two Cultures dichotomy. However, contemporary product designers are increasingly striving to create tools that possess both functionality and beauty. This perspective raises concerns for visualization design, as the pursuit of aesthetic appeal could potentially overshadow the primary goal of facilitating understanding. Lima strongly contends that merely presenting data visually without providing insight into the subject matter or unnecessarily complicating it constitutes a failure.[248] Hence, if what we produce lacks both beauty and usefulness, it can be deemed a complete failure. This raises the question: *What role should aesthetics play in the realm of sonification design?*

Aesthetics is commonly defined today as the philosophical exploration of art and the principles, ideas, and varieties of experiences associated with art, such as taste, beauty, and the sublime.[249]

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[244] Redström, 2008, pp.1

[245] K.Card, Mackinlay, & Shneiderman, 1999, pp.6.

[246] Redström, 2008. pp.2

[247] "We can forgive a man for making a useful thing as long as he does not admire it. The only excuse for making a useless thing is that one admires it intensely. All art is quite useless.", Oscar Wilde, The Picture of Dorian Gray (1890). See Wilde, 1992.

[248] Lima, 2009.

[249] Isaacs, Martin, Law, Blair, Clark, & Amanda Isaacs (eds), 1998.

The term "aesthetics" originates from a broader Greek root related to perception and sensation, and before the mid-eighteenth century, aesthetics constituted a branch of philosophy concerned with sensory perception.[250] Notably, the term "anaesthetic" literally denotes the absence of sensation. Synaesthesia (derived from the same root) refers to the blending of senses in perception (e.g., associating colors with sounds). In the mid-eighteenth century, German philosophers initiated a movement to address issues of taste, beauty, and the sublime. In 1750, Baumgarten defined aesthetics as the act of judgment through or by means of the senses. Through the contributions of Baumgarten's successors—Kant, Schiller, Schelling, and Hegel—a significant shift occurred by the end of the nineteenth century, resulting in a modern conception of aesthetics. According to Nake and Grabowski,[251] this modern understanding prominently emphasizes beauty.

Rose-Coutre characterizes art as an object primarily concerned with aesthetic appeal and sensory engagement.[252] In Kantian philosophy, the focus lies on the capacity to form judgments of beauty, with aesthetics residing within the domain of sensibility. Aesthetic experience, according to Kant, necessitates both intuitive and conceptual elements.[253] Kant's framework intertwines perception and understanding, emphasizing their inseparability. Hegel, expanding upon Kant's theories, defines art as a sensory medium for conveying ideas, bridging concepts with our sensory perceptions and rational faculties.[254] Unlike Wilde's notion of art for art's sake, Hegel opposes this concept, viewing art as a vehicle for expressing truth through beauty. He contends that the essence of art lies in its ability to present beauty, emphasizing that beauty encompasses both form and content.[255]

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[250] The etymological root of aesthetics is the Greek word αίσθάνομαι meaning "I perceive, feel, sense", See Harper, http://www.etymonline.com.

[251] Nake and Grabowski, 2006, pp. 54

[252] Rose-Coutré, 2007, pp.5

[253] Burnham. 2010.

[254] de Botton, 2011.

[255] Houlgate, *Stanford Encyclopedia of Philosophy*.

In recent times, there has been a notable resurgence of aesthetic considerations within the realms of data visualization, data aesthetics, and the Creative Commons. Over the past half-decade, there has been a widespread adoption of computational tools, technologies, and methodologies that were once confined to specialized domains such as institutional labs at NCSA, NASA, CSIRO, and others. The advent of open-source platforms like Processing[256] and Many Eyes[257] has democratized visualization, expanding its scope into artistic endeavors, advertising, DIY online culture, and various communities with diverse objectives, languages, and evaluative criteria (e.g., affect, social significance, narrative, production quality, etc.), often collectively referred to as "aesthetics."

Lima's manifesto serves as a notable illustration of the initial phase, emphasizing the paramount importance of functionality. Lima even characterized himself as "a functionalist troubled by aesthetics."[258] Within this initial phase, Carroll succinctly encapsulates the inherent risk in visualization:[259]

> To some extent however this elegance, which makes data visualisation so immediately compelling, also represents a challenge. It's possible that the translation of data, networks and relationships into visual beauty becomes an end in itself and the field becomes a category of fine art. No harm in that perhaps. But as a strategist one wants not just to see data, but to hear its story. And it can seem that for some visualisations the aesthetic overpowers the story.

Meanwhile, proponents of the 'second wave,' exemplified by figures like Vande Moere, have embraced aesthetics as a pivotal element in visualization endeavors, referring to concepts such as 'information aesthetics,' 'information aesthetic visualization,' and 'artistic data visualization.' They view this 'second aesthetic turn' as a bridge between information visualization and data art, emphasizing the necessity for interdisciplinary approaches. Echoing sentiments akin to those of Hegel and the initial aesthetic movement, Lau and Vande Moere assert that information aesthetics 'employs more interpretative mapping techniques to enhance information visualization

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[256] See http://www.processing.org

[257] See Many Eyes

[258] See Justin McMurrary's blog of 3 September, 2009 at https://www.madebymany.com/ (accessed April, 31)

[259] Carroll, 2009.

with external significance, or incorporates functional elements in visualization art to more efficiently convey the underlying meanings of datasets.'[260]

As an illustration of interdisciplinary collaboration, consider the work of Keefe et al.,[261] who documented two collaborative visualization endeavors involving computer scientists and artists aimed at crafting effective representations. They introduce a continuum of representation (refer to Figure 7), ranging from visualizations typically classified as information art on the left to more conventional information visualizations on the right. This spectrum serves not to segregate or delineate disciplines, but rather to demonstrate the validity and significance of expressions at both ends (and all points in between). It emphasizes the importance of collaboration between artists and researchers in developing novel techniques and representations.

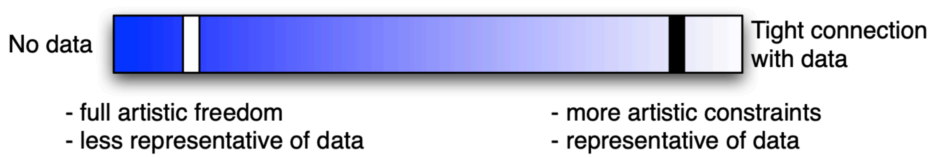

Figure 7: *Adapted from Keefe et al., shows that systems with a tight connection to underlying data are highly indexical. Indexicality in visualization. The black and white bars indicate visualization tools operating at different ends of the representational continuum. The white bar is a system that is informed by underlying data but in which artistic freedom is the main driver. The black bar would be the position of a system in which artistic expression is much more tightly constrained with the focus being clear representation of a data set.*

Vickers and Hogg[262] introduced the concept of indexicality to discussions surrounding sonification.[263] Indexicality refers to something—a gesture, an utterance, a sign, etc.—that points to or indicates some external thing, whether an entity or an idea. In sonification practice,

[260] Lau & Vande Moere, 2007.

[261] Keefe, Karelitz, Vote & Laidlaw, 2005.

[262] Vickers & Hogg, 2006.

[263] Indexicality is a concept from philosophy which is often used interchangeably with the linguistics term *deixis* and is also used in semiotic explanations of *sign*.

indexicality serves as a gauge of the degree of arbitrariness in a mapping; in semiotic terms, an indexical signifier lacks arbitrariness and directly connects, either physically or causally, to what it signifies.[264] In sonification, it is either the data itself that generates sound (parameter-based sonification) or user interactions with the data that produce sound (model-based sonification). A sonification system characterized by high indexicality generates sound directly from the data, such as through direct data-to-sound mappings. Conversely, low indexicality arises from more symbolic or interpretative mappings.

Keefe et al.[265] demphasize the importance of involving artists and visual designers in visualization projects from the initial design phase rather than simply employing them to adjust existing visualization techniques.[266] They argue that artists offer valuable visual insights and creative solutions for complex visual challenges beyond mere aesthetic enhancements. Integrating functionality and aesthetics poses an enriching challenge for them. The collaboration between artists and computer scientists within the constraints of data mappings and visual design prompts the development of innovative visualization techniques and hypothesis reevaluation. An illustration of this collaboration is evident in Stallman et al.[267] use of a composer to aid in the design of an auditory display for an automated telephone queue management system.

4.1.3.2: Aesthetics as principles

Aesthetics, or the framework of aesthetic perception, serves as the basis for evaluating artistic works. When the term "aesthetic" is mentioned alongside sonification or auditory display, there's often an immediate assumption that the discussion pertains solely to artistic qualities. Similar to the stance taken by early advocates of visualization, there's an argument that sonification belongs to the realms of science and engineering, and thus, should not be approached as art. However, this presents a false dichotomy rooted in the misconception that art and science are inherently

[264] Chandler, 2007.

[265] Keefe, Karelitz, Vote & Laidlaw, 2005.

[266] Keefe et al., 2005, pp. 23

[267] Stallmann, Peres & Kortum, 2008.

incompatible. The crux of the matter lies in the understanding that aesthetics transcends the confines of art; it fundamentally revolves around sensory perception.

Whitehead's assertion regarding art as the imposition of a pattern on experience, with aesthetic enjoyment stemming from recognizing the pattern[268] suggests that while aesthetic judgment is crucial for enjoying art, the presence of patterns implies the possibility of harnessing aesthetics in the design and implementation of visualization systems primarily aimed at gaining insights from data. Nake and Grabowski[269] extend this idea by emphasizing that aesthetics, concerned with sensory perception, prioritize questions of perception over beauty. Graves Petersen et al.[270] echo this sentiment, contending that those who limit aesthetics to providing visually pleasing products overlook its broader potential. They argue that aesthetics should not be viewed merely as an added enhancement or superficial attraction, but rather as an integral aspect of understanding interactive systems and their potential applications.[271]

In mathematics, aesthetics has long been recognized as a significant factor. Mathematicians aim to simplify the description of objects or phenomena, whether for the sake of simplicity itself or to facilitate calculations for real-world applications. Einstein prioritized mathematical elegance and simplicity in his approach, while physicist Paul Dirac expanded on this notion with his "Principle of Mathematical Beauty," asserting that theories reflecting the complexities of nature are inherently beautiful, and that elegance is indicative of correctness. Thus, in the realm of mathematics, truth and beauty are interconnected: beauty unveils truth, and truth is inherently beautiful. However, the pursuit of beauty in mathematics is not purely for its own sake; rather, simplicity, or beauty, enhances understanding more readily.

To provide a practical illustration, when evaluating the aesthetics of graph drawings, factors such as the number of edge crossings (less is preferred) and the degree of symmetry in the graph

[268] Whitehead, 1996.

[269] Frieder Nake and Susanne Grabowski, 2006, pp.62

[270] Petersen, Iversen, Krogh, and Ludvigsen, 2004, pp. 270

[271] Petersen, Iversen, Krogh, and Ludvigsen, 2004, pp. 271

(more symmetry is desirable) are considered[272] as they directly influence the graph's readability. Thus, aesthetics involve making judgments based on sensory perception, and the more conducive a representation is to such judgments, the better it is considered. However, it's important not to assume that beauty necessarily implies interest. In discussing his research on algorithms for creating visually straightforward ("simple") art, Schmidhuber emphasizes this distinction:

> Interest has to do with the unexpected. But not everything that is unexpected is interesting — just think of white noise. One reason for the interestingness (for some observers) of some of the pictures shown here may be that they exhibit unexpected structure. Certain aspects of these pictures are not only unexpected (for a typical observer), but unexpected in a regular, non-random way.[273]

In alignment with Keefe et al.[274] acknowledgment of the intricacies in visualization design, there exists a similar tension in crafting auditory representations, where aesthetic and artistic expression must navigate within the confines of computational challenges in data mapping. Addressing the realm of sonification design, Vickers emphasized:

> The larger questions of sonification design are concerned with issues of intrusiveness, distraction, listener fatigue, annoyance, display resolution and precision, comprehensibility of the sonification, and, perhaps binding all these together, sonification aesthetics.[275]

Pedersen and Sokola[276] pointed out that a lack of aesthetic quality contributed to the rapid disinterest in the sonifications employed within their Aroma system.[277] Kramer in agreement, stated that some of his sonification experiments were unappealing. He referenced Gaver's observation that SonicFinder was often disabled, Mynatt's report of poorly crafted sounds diminishing Mercator's effectiveness, and his own acknowledgment of the aesthetic shortcomings in his work.[278]

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[272] Andrea Lau & Andrew Vande Moere, 2007

[273] Jürgen Schmidhuber, 1997, pp. 102

[274] Keefe, Karelitz, Vote, and Laidlaw, 2005

[275] Paul Vickers, 2006, pp.57

[276] Pedersen & Sokoler, 1997

[277] Vickers, 2006

[278] Kramer, 1994, pp.52

4.1.3.3: A approach in pragmatism

If we acknowledge that aesthetics extends beyond traditional art forms, particularly in the context of sonification (and visualization more broadly), we may assert that aesthetics is not exclusively tied to art.[279] This perspective suggests that constraining aesthetics to the assessment of artistic value and taste is counterproductive in this context, as it restricts our possibilities and shifts our focus away from exploring the potential of aesthetics in designing effective sonifications that facilitate comprehension, insight, and pattern recognition. Rather than solely serving as a pinnacle of artistic expression, good aesthetic principles in sonification aid in achieving user-friendliness, a concept Manovich describes as "anti-sublime".[280] Contrary to the Romantics' emphasis on the sublime, which encompasses phenomena surpassing human sensory and rational limits, visualization systems are inherently anti-sublime as they aim to render underlying datasets representable.

The inquiry arises: how can aesthetics be incorporated or utilized in the creation of sonifications? For mathematicians, aesthetics encompass notions such as invariance, symmetry, simplicity, proportion, and harmony[281] offering avenues for exploration within mathematical frameworks. In physics, aesthetics often involve employing symmetries to represent preceding generative states.[282] In sonification design, akin to the challenges encountered by creators of interactive computer systems aiming for a favorable user experience, we confront similar hurdles. The conundrum lies in the impossibility of directly crafting a user experience;[283] instead, one can only design with the user experience in mind. In aesthetic discourse, this dichotomy manifests as the distinction between analytic and pragmatist aesthetics. According to Moore's[284] analytical

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[279] Aesthetics extends beyond art in the same way that a painting surpasses mere technological and chemical processes involved in pigment design and production, although they are intricately linked. Art cannot exist without the supporting technology, and meaningful or practical visualization is impossible without aesthetic considerations.

[280] Lev Manovich, *The anti-sublimei deal in data art*

[281] Fishwick, 2006, pp.9

[282] Leyton, 2006, pp. 307

[283] Sharp, Rogers & Preece, 2007, pp. 15

[284] George Edward Moore, 1993

perspective, aesthetics are entities unto themselves, perceptible to a viewer on an intuitive level.[285]

In this framework, aesthetic qualities emerge as the artist or designer crafts an artifact, anticipating discovery by the viewer/user, suggesting an inherent objective existence. This aligns with the notion that a software designer can aim for a universally shared user experience. However, the analytical perspective overlooks socio-cultural influences on how an artifact is perceived,[286] or experienced, as Dewey's[287] terminology suggests.[288] Graves Petersen et al. note these factors as well:

> Dewey insists that art and the aesthetic cannot be understood without full appreciation of their socio-historical dimensions [. . .] that art is not an abstract, autonomously aesthetic notion, but something materially rooted in the real world and significantly structured by its socio economic and political factors.[289]

Dewey's pragmatic perspective acknowledges that aesthetic encounters emerge from the holistic engagement of individuals within a given context.[290] This pragmatic approach to aesthetics leads us to accept that user experiences can only be designed for to a certain extent, emphasizing the importance of facilitating meaningful dialogue with our sonifications while acknowledging the inevitability of variability in experiences. Sonification involves users in a process of making sense, underscoring the need for designers to recognize that users' interactions with systems are shaped not only by immediate sensations but also by past experiences and socio-cultural influences.[291] As Sharp et al. articulate, while it is impossible to directly design a sensory experience, designers can create design elements that have the potential to evoke such experiences.[292] Wright et al. further suggest that since designers cannot fully construct aesthetic

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[285] Petersen, 2004.

[286] Petersen, 2004.

[287] Dewey, 2009.

[288] Also see Macdonald, 2002.

[289] Petersen, 2004, pp. 271

[290] Wright, Wallace & Mc Carthy, 2008, pp. 4

[291] Petersen, 2004, 272

[292] Sharp, Rogers & Preece, 2007, pp. 15

experiences or exert significant control over user experiences, their role is to furnish resources that enable users to structure their own experience.[293]

In the pragmatist perspective, aesthetics is conceived as an experiential phenomenon arising from the interplay between the user and the contextual factors, encompassing cultural and historical dimensions. This viewpoint posits that aesthetics cannot be solely attributed to either the artifact or the observer. Rather, it acknowledges that the interaction is co-constructed by both the user and the designer, and that the process of making sense involves not only cognitive faculties but also the sensory and emotional aspects of experience situated within specific temporal and spatial contexts.[294] In Kant's aesthetic framework, the beauty of an object is not an inherent property of the object itself, but rather emerges through our responsive engagement with it. According to Kant, beauty is intimately tied to the form of an object.[295]

4.1.3: Sonification Aesthetics

If we acknowledge the importance of considering aesthetic in sonification design and admit that frameworks like pragmatist aesthetics provide valuable perspectives for conceptualizing our aesthetic endeavors, we are confronted with the query: what exactly constitutes sonification aesthetics? How do they manifest audibly? Are there particular principles that, if systematized, can ensure (or at least enhance the likelihood of) achieving aesthetic success?

It has been noted that numerous codified aesthetics often present contradictions, making it impractical to achieve all of them in a single work.[296] Additionally, sonification is not a distinct, isolated discipline; it intersects with perceptual psychology, computer science, engineering,

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[293] Wright, Wallace & Mc Carthy, 2008, pp. 9-10

[294] Wright, Wallace & Mc Carthy, 2008, pp. 18

[295] For Kant, beauty was universal (or rather that which one would perceive as beautiful one would assume is a universal response even though it might not be in reality) but the perception of beauty is arrived at through a disinterested inspection. By that Kant means that the judgment is made independent of any interest we might have in the object, independent of its content, its moral or financial value, etc. The judgment of beauty is made only in terms of the object's form (its shape, its composition, its texture, etc.).

[296] Quigley, 2006.

sound design, and sonic art, drawing upon a variety of skills from these fields and potentially others. Sonification encompasses diverse styles employing various sonic techniques, each with its own distinct set of aesthetic principles. For instance, in the realm of musical renderings, inspiration from musical practices reveals a plethora of genres, each governed by its own aesthetic conventions.

Vickers and Hogg[297] proposed a conceptual framework termed aesthetic perspective space (refer to Figure 8), wherein sonifications are linked to their closest counterparts in the realm of music. The underlying notion is that if a sonification is structured akin to a tonal music piece, it could leverage the aesthetics inherent in tonal musical composition, provided an appropriate subgenre is identifiable. Similarly, a sonification organized in the manner of musique concrète could tap into electroacoustic aesthetics. However, it is essential to note that each musical style possesses its own distinct aesthetic characteristics.

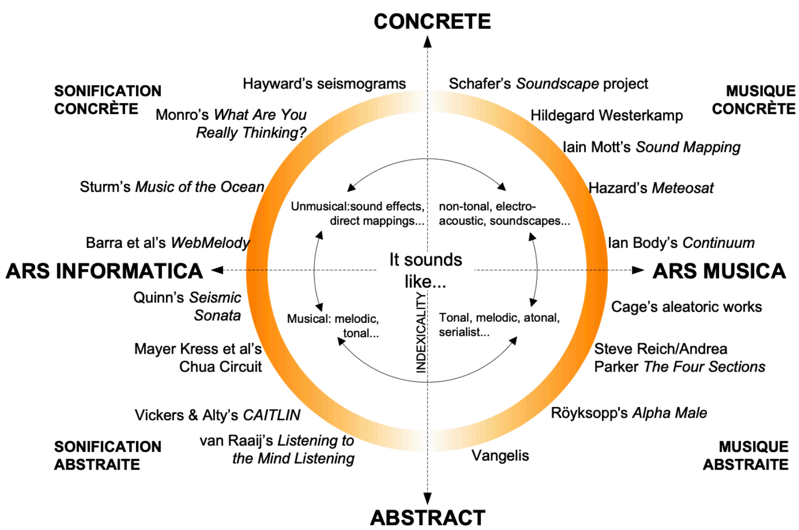

Figure 8: *The Ars Musica — Ars Informatica Aesthetic Perspective Space.*

Sonification aesthetics is a relatively unexplored area in research, lacking comprehensive investigations, and thus, there is no definitive set of aesthetic principles established. The feasibility or desirability of formulating such guidelines remains uncertain. In alignment with

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[297] Paul Vickers and Bennett Hogg, 2006.

their exploration of aesthetic interaction design, Wright, Wallace, and McCarthy argued against the notion of delineating principles or guidelines for crafting captivating experiences.

Furthermore, as noted by Roads, an aesthetic philosophy can be understood as a compilation of concepts and preferences guiding an artist's decision-making"[298] process. Therefore, it's crucial not to treat any set of aesthetic principles as absolute and unchangeable. Even if aesthetics could be systematized, they still demand inherent talent and acquired skill for their execution; the talent being innate and the skill being imparted through teaching or other means. Additionally, any proficient practitioner must possess the understanding of when and how it's appropriate to deviate from these guidelines.

Barass and Vickers contended that enhancing the aesthetic quality of sonifications hinges on the proficiency of designers-artists in aesthetic thinking and practice or collaboration with individuals possessing such expertise. Recent trends indicate the emergence of advanced university courses integrating art and technology, equipping individuals with literacy and proficiency in both domains. This underscores the notion that technologists can acquire aesthetic skills akin to artists learning coding. However, these courses necessitate a deliberate commitment to interdisciplinary collaboration, echoing Kramer's advocacy for interdisciplinary endeavors. Kramer urged collaboration with composers, sound designers, and other sound artists to achieve the overarching goal of producing auditory representations that illuminate underlying data or realities, facilitating inference and comprehension.

4.1.4: Future Directions

In sonification, the necessity for melding function and aesthetics is heightened and challenging, particularly as compared to graphical visualization, where concrete evidence of insights from auditory representations is less prevalent. This challenge is underscored by the profound affective and cultural dimensions of sound, which we often perceive through our musical

[298] Curtis Roads, 2004, pp. 326

education and experiences. *How can one create sonifications that are both affective and convincing?*

The inquiry into the correlation between beauty and functionality arises in discussions surrounding both sonifications and graphical visualizations. This is an area where the application of design thinking and aesthetic principles could be beneficial. As depicted in Figure 9, aesthetics, defined as sensuous perception, serves as a unifying element in both sonic art and sonification. Aligning with the conclusion drawn by Barrass and Vickers, there appears to be an unnecessary division between sonic art and sonification. They argue that approaching sonification as a genuinely interdisciplinary design process holds significant potential for enriching the work of the auditory display community as it progresses and evolves.

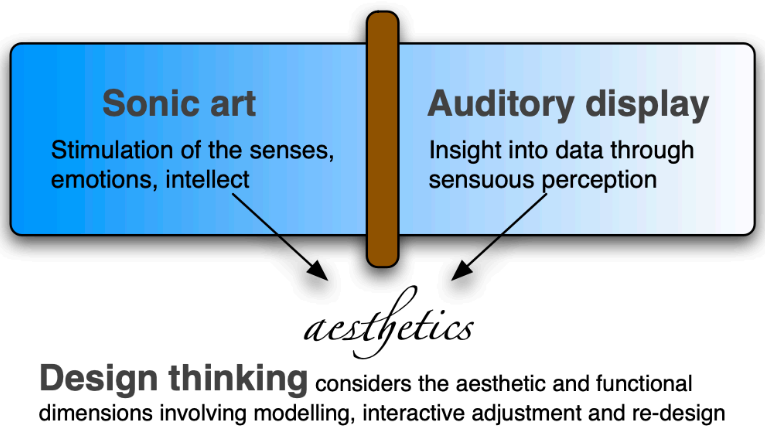

Figure 9: *The wall between sonic art and sonification/auditory display is a false one. Aesthetics is a framework for working across the spectrum.*

A design-centric approach also transitions sonification away from engineering paradigms of information transmission toward cultural communication theories. Expanding on this concept, Schertenleib and Barrass[299] are elaborating on the notion of sonification as a social platform through the Many Ears platform designed for a community of practice in data sonification.[300]

[299] Anton Schertenleib & Stephen Barrass, 2010

[300] See Many Eyes

This platform draws inspiration from Many Eyes, a collaborative visualization and exploration site, merging elements of a social networking platform with online tools for visualizing data.[301] Users are empowered to upload datasets, provide descriptions, and share them for visualization or download by others. The user-friendly interface and social components of Many Eyes have attracted a diverse audience, leading to the emergence of unexpected political, recreational, cultural, and spiritual applications distinct from traditional data analysis. The Many Ears initiative aims to explore the potential outcomes when data sonification becomes more accessible as a mass medium. *What demographics will engage with sonifications? Who will create? and who will benefit from sonified data? What unforeseen applications will emerge from sonification?*

Kramer's 1994 proposition (subsequently reiterated by Vickers a decade later)[302] advocating for the involvement of composers in the process of sonification design remains as pertinent today as it did then, encompassing not only sound artists and designers but also professionals in film sound and interactive product design. Presently, there appears to be considerable potential for sonification to serve as a conduit for conveying data-related information to a wide audience of music enthusiasts, who also seek aesthetically gratifying experiences. A constructive path forward entails an inclusive approach that avoids oversimplifying the relationship between art and science. Design thinking necessitates acknowledging the existence of multiple constraints and solutions within any problem domain. A successful solution is one that addresses the objectives of the project, which may entail both qualitative and quantitative considerations, while also taking into account the specific context and audience.

Sonification represents a captivating domain situated at the crossroads of forthcoming advancements in music, design, and science, and I am eager to witness the developments in these areas.

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[301] http://www-958.ibm.com/software/data/cognos/manyeyes/

[302] Gregory Kramer, 1994. Also Paul Vickers, 2004.

4.2: Sonification As Art

4.2.1: Introduction

One interesting aspect of sonification lies in the nature of the data it employs. Whether it's financial figures or temperature fluctuations, these data sets are typically numerical in form. Sonification practitioners take these numerical data points and imbue them with new significance, often diverging from their original intended purpose. This reinterpretation can offer fresh perspectives, sometimes unrelated to the data's original context, though there are often valid reasons for maintaining such connections. For instance, when crafting a piece inspired by seismic activity following an earthquake, the artwork assumes a dual role: as both a subject for artistic exploration and expression, and as a vehicle for raising awareness about seismic events. Likewise, incorporating climate data into an artistic endeavor can serve to underscore issues surrounding climate change for the audience.[303]

Nevertheless, artists may opt to use data solely as control parameters for an artwork that is disconnected from the original significance of the data. In such instances, the artist's primary objective is to craft a visually and aesthetically captivating piece without direct relevance to the underlying data. This represents a personal decision for the artist, who may adopt this approach to challenge traditional interpretations of data, experiment with novel modes of visual and auditory expression, or incite contemplation and discourse on the role of data in contemporary artistic practice.

[303] An exemple of this phenomenon can be found in the artistic endeavors of Chris Jordan and Olafur Eliasson. Jordan, for instance, employed seismic activity data to craft visual depictions of earthquake repercussions in his series 'Seismic Shifts.' Similarly, Eliasson's installation 'Ice Watch' showcased ice blocks sourced from Greenland's melting glaciers in public settings, aiming to highlight the ramifications of climate change

4.2.2: Sonification Art: Mapping Problem

When employing sonification for artistic purposes, the choice of a suitable mapping technique holds significant importance. This issue of identifying the most suitable mapping method is often termed as the "mapping problem" within this context.[304]

Polansky characterizes the mapping problem as the conversion of an idea from one domain to another. The difficulty lies in translating non-musical data into musical components such as pitch, amplitude, and timbre. Due to its artistic nature, this problem lacks a direct resolution, primarily because artistic expression often involves subjective and intricate interpretations that defy easy quantification or standardization. This variability arises from individual perspectives, cultural influences, personal histories, and creative decisions, rendering it difficult to establish a consistent and universally accepted mapping methodology.

To understand the mapping problem, let's examine a historical instance. Charles Dodge's composition "Earth’s Magnetic Field"[305] is frequently cited as a case of sonification within algorithmic composition.[306]. Dodge characterizes it as a musical portrayal of values reflecting the sun's radiation effects on Earth's magnetic field.[307] There exist several valid methods for mapping these magnetic field values to musical components. The difficulty lies in interpreting these values and determining their musical representation. This exploratory process, where different musical interpretations are investigated based on the same data, embodies musical sonification. Dodge's composition culminates in his decision to map the 28 index values to a four-octave diatonic scale in C using a meantone temperament.[308]

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[304] Larry Polansky, 2002. Also see section “3.1.2.1: mapping in sonification” of this chapter

[305] Dodge, 1970.

[306] See for example, Childs, 2003.

[307] Dodge and Jerse, 1997.

[308] Dodge and Jerse 1997.

Polansky introduces the term "manifestation" to describe artistic sonification, wherein a formal or mathematical procedure generates a novel musical concept.[309] Additionally, he categorizes sonification and manifestation separately.[310] Sonification aims to audibly represent a process to enhance comprehension, primarily serving educational and illustrative purposes. For instance, the sonification of helicopter flight data enables the detection of anomalies through changes in sound. Conversely, manifestation focuses on crafting an aesthetic experience or composition. Although alarm or status sounds may possess some aesthetic attributes, their principal purpose remains utilitarian. (See figure 10)

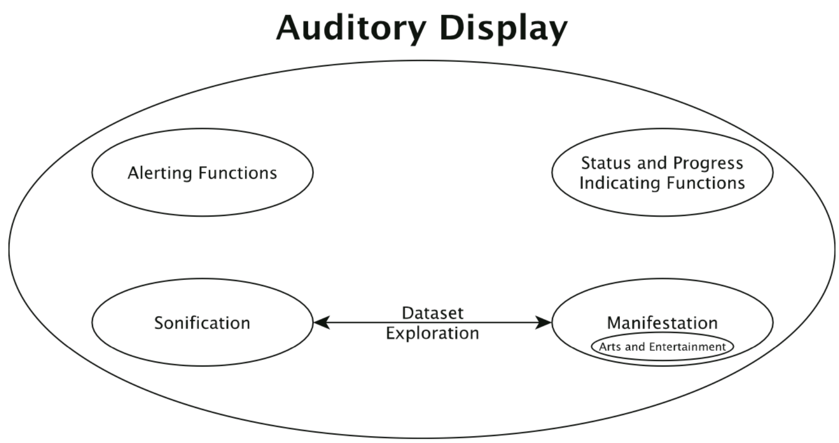

Figure 10: *Polansky (2002) distinguishes between a Sonification subset and a Manifestation subset. Sonification and manifestation are connected through the dataset exploration function.*

Polansky further makes a distinction between manifestation and algorithmic composition, where the latter entails the application of a precise and well-defined algorithm to the music composition process.[311] In subsequent sections, we will delve into these concepts by conducting methodical examinations in the field of musical sonification.

[309] Polansky, 2002.

[310] Otherwise refered to as "scientific sonification" and "artistic sonification".

[311] Jacob, 2000.

4.2.3: Sonification and Algorithmic Composition

In this section, our focus is on discussing the artistic potential of sonification. We particularly emphasize the correlation between artistic sonification (referred to as manifestation by Polansky) and algorithmic composition, while also drawing attention to their distinctions.

Algorithmic composition employs non-musical procedures to produce music by translating data onto musical characteristics. It entails generating music using algorithms or guidelines governing aspects like pitch, rhythm, and arrangement. This approach is not novel; as far back as the 14th century, Guillaume Dufay utilized proportions from the Santa Maria del Fiore cathedral in Florence to determine the tempi in his motet *Nuper Rosarum Flores*.[312] In a similar vein, Mozart's *Musical Dice Game* utilized matrices containing musical snippets, wherein each roll of the dice generated a unique sequence of numbers corresponding to these snippets, resulting in fresh compositions that remained rooted in tonal principles. In the 20th century, composers such as Iannis Xenakis, Lejaren Hiller, and Gottfried Michael Koenig embraced algorithmic methods in their music, marking a departure from conventional norms in pursuit of more experimental approaches that introduced novel musical frameworks and questioned established ones.

Numerous approaches exist for algorithmic music composition. Roads distinguishes these approaches into two primary categories: stochastic and deterministic music. Likewise, Maurer delineates between stochastic music, which employs computer-generated numerical sequences with a degree of flexibility in their application to musical components, and rule-based (or deterministic) music, wherein predetermined rules govern the composition process.[313] An example widely cited in the realm of deterministic music is the treatise on counterpoint, *Gradus ad Parnassum* by Fux (1965). Supper provides a more nuanced categorization of deterministic music, outlining three distinct types:

1. Adapting traditional compositional techniques.
2. Innovating novel compositional approaches separate from established methods.

[312] Taube, 2004.

[313] Roads, 1996 & Maurer, 1999.

3. Integrating algorithms alongside non-musical processes.[314]

McKay and Schottstaedt provided illustrations of the initial category, labeled as, “Modelling traditional compositional methods.”[315] For instance, Ebcioglu pioneered *Choral*, a software intended to generate harmonies reminiscent of Bach's style.[316] Another instance is the *Illiac Suite*, crafted by Lejaren Hiller and Leonard Isaacson in 1957, employing algorithms to emulate conventional composition techniques.

Clarence Barlow's *Çogluotobüsisletmesi* epitomizes the second category.[317] In this case, algorithms dictate elements such as rhythm, melody, chord density, and articulation. The resultant piece emerges as a structured composition, with its ultimate form being just one among numerous potential outcomes.[318]

The third category incorporates non-musical processes for material generation. One notable method is the Lindenmayer system (or L-system), which was introduced by Aristid Lindenmayer in 1968. Originally developed to describe plant cell behavior, this system has found application in modeling various growth phenomena. An L-system consists of an initial axiom and a set of rules for rewriting. For instance, consider an axiom denoted by 'X' and a rule dictating the transformation of 'X' to 'XYX'. Through iterative application of this rule to the axiom, a distinct pattern gradually emerges:

X
XYX
XYXYXYX
XYXYXYXYXYXYXYX
XYXYXYXYXYXYXYXYXYXYXYXYXYXYXYX

[314] Supper, 2001.

[315] McKay, 2002 & Schottstaedt, 1984.

[316] Ebcioglu, 1990.

[317] Clarence Barlow, 1980.

[318] Supper, 2001.

An intriguing characteristic of L-systems is their tendency to generate repetitive patterns as the system iteratively applies its rules. Several composers, including Hazard et al.,[319] Sodell, and Soddell,[320] have explored the use of L-systems in their compositions.

Within the realm of algorithmic music, determining the placement of Polansky's "manifestation" presents a distinctive challenge due to the dynamic nature of data. Especially in real-time musical compositions, employing fixed rules for manifestation proves to be difficult. An adaptable approach becomes crucial, enabling rules to swiftly adjust to the changing data: One approach is to utilize interactive dynamic system, which users can manipulate in real-time.[321]

When addressing the classification of manifestation in algorithmic music, two key hurdles come to the forefront: firstly, the utilization of real-world data versus mathematical models, and secondly, the revelation of distinct patterns only post data generation; "Patterns emerge but we can only see them after the data have been created. There is a certain degree of information entropy."[322] These intricacies render existing classifications such as stochastic or deterministic insufficient. In response to these challenges, S. Van Ransbeeck proposes a novel classification: "Sonification Art" (See Figure. 11).

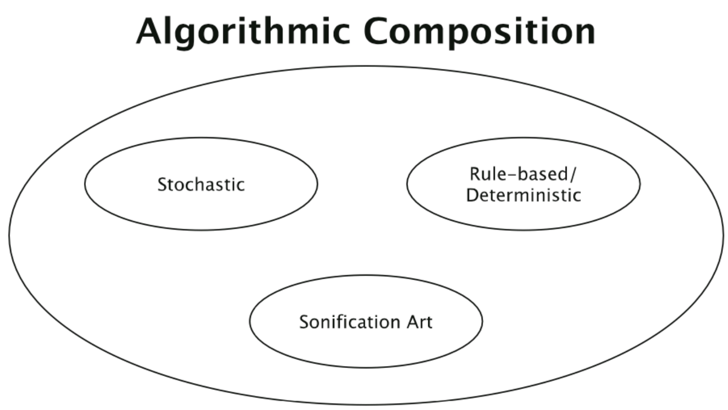

Figure 11: *Sonification art; the third type of algorithmic composition*

[319] Hazard, C., Kimport, C., & Johnson, D. *Fractal Music*.

[320] Sodell, J., & Soddell, F. Microbes, *L-systems and music*.

[321] S. Van Ransbeeck, 2018.

[322] Van Ransbeeck, 2018.

4.2.4: Definition of Sonification Art

Having explored auditory displays and algorithmic music individually, we can now combine these concepts to delineate the role of sonification art within these frameworks. In preceding chapters, the classification by Walker and Nees identified arts and entertainment as a category for the application of sonification. It is crucial to recognize, however, that while algorithmic composition belongs to the general field of arts, not every piece of algorithmic music qualifies as sonification (See Figure: 12).

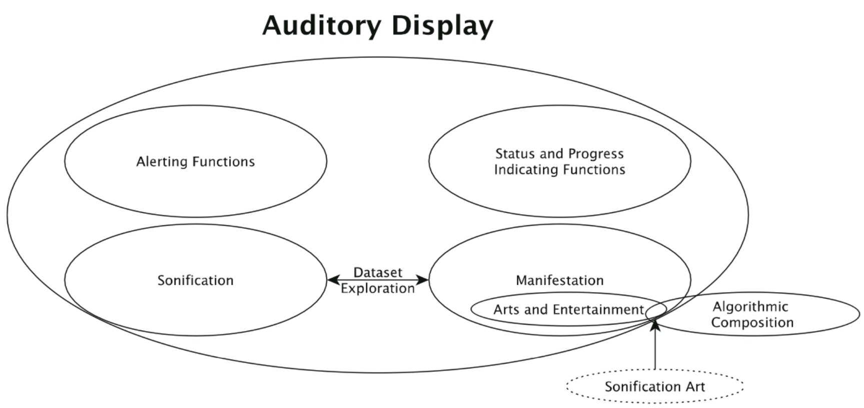

Figure 12: *The connection between algorithmic composition and sonification on the auditory display map is noteworthy. Sonification art is positioned at the intersection of arts and entertainment and algorithmic composition.*

4.2.4.1: To establish a definition

In previous sections, I emphasized the differences between science and art regarding their objectives and methodologies related to data. An essential element of artistic practice that has not yet been addressed is the artist's innovative use of data, which incorporates both subjective and creative aspects. When artists convert observational data from natural phenomena into musical parameters, they might initially find the results unsatisfactory. In such instances, adjustments can be made to enhance the composition. For example, if a sequence of values shows an upward trend but one value disrupts the pattern, leading to an inconsistent melody, the composer might alter that value to achieve a smooth flow. This process, known as "data reinterpretation," acts as a creative catalyst in sonification.[323]

Creativity is fundamental to the process of sonification. In this regard, Van Ransbeeck uses Polansky's term "manifestation" to describe the inherent creative element in sonification. He defines the concept of sonification within an artistic context as follows:

> Sonification art is an arts practice that uses data from observations of world phenomena, which are mapped onto musical parameters through fixed or dynamic mapping procedures as an essential input element and that uses sound to manifest itself.[324]

4.2.5: Sonification Process and Interpretation of Data

The sonification process can be outlined in three main stages:

1. Data collection
2. Data interpretation
3. Auditory representation of the data.

When discussing sonification, it is essential to begin with the analysis of the source material or data. Virtually any dataset, such as seismic, weather, or financial data, can be used for sonification, and many of these datasets are readily available online.[325] The critical factor is to choose a dataset with sufficient variability for effective sonification. For example, the birth rate of the dodo over 200 years, which remains constant, would not be an interesting choice. On the other hand, a series of purely random numbers would provide an excessive amount of data, leading to a highly dynamic sonification. Therefore, selecting the right dataset is crucial.

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[323] Xenakis illustrates this approach to localized decision-making in his compositions, notably in the piece "Herma" (Bayer 2000).

[324] Playful Disruption of Digital Media, pp.157

[325] Either accessible at no cost through platforms such as http://www.data.gov or available for acquisition through marketplaces like the Microsoft Azure Data Marketplace.

The second phase entails determining the methods for data storage and retrieval. We need to decide between real-time data generation and previously stored data, each option having its own advantages and disadvantages. Live data streams bring about unpredictability,[326] as interactions among elements result in unique patterns. Consequently, our mapping strategy must remain adaptable. This adaptability can be integrated in two ways:

1. During the conceptual phase, by exploring various mapping techniques.
2. During the presentation phase, by allowing user interaction within a predefined framework.

When working with a recorded dataset, it can be reviewed multiple times, allowing for adjustments to the mapping method. In contrast, real-time data does not permit repeated examination. However, in both scenarios, artists have the option to allow user influence over the data and mapping decisions. Additionally, the aesthetic quality of the artwork is important, particularly if long-term user engagement is desired. As Kramer observes, enhanced aesthetics will probably minimize display fatigue.[327]

In the third phase, emphasis is placed on auditory depiction. The composer delineates the characteristics of the sound, whether by composing a musical score for acoustic instruments or by linking data to synthesis parameters. As mentioned by Mazolla,[328] the composition functions as a "directive framework for generating audible music," enabling the performing musician to exercise individual discretion.

These stages do not necessarily follow a linear progression; modifications may take place at any stage, highlighting the interrelatedness of the process and the resulting product. Moreover, the ultimate goal is to interpret data for scientific, artistic, commercial, or political objectives. While scientific interpretation focuses on clarity of information, artistic representation prioritizes

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[326] In his examination of urbanism, Devisch (2008) refers to this type of behavior as Organized Complexity. Through a range of interactions, the individual components produce a unique macro-behavior, resulting in identifiable patterns or configurations (Johnson 2003).

[327] Kramer, 1994.

[328] Mazolla et al., 2011.

aesthetic experience. Nonetheless, even within scientific domains, aesthetics hold importance, affecting audience engagement or fatigue levels.

4.2.6: Creative Processes in Sonification Art

The advent of conceptual art in the 20th century has shifted focus from the final artwork to the process of its making. Danto coins the term "post-historical" to delineate the period from around 1950 onward, signifying a departure from art's linear advancement through history, during which "art was no longer possible in terms of a progressive historical narrative.”[329]

He exemplifies this transition using Andy Warhol's *Brillo Box*, initially designed as a vessel for cleaning pads. Warhol's reinterpretation of this commonplace item as art highlights the dominance of idea over materiality. Through the re-contextualization of the *Brillo Box*, Warhol bestowed upon it fresh artistic importance, dissociating it from its initial function.

Likewise, in sonification art, data undergo a transformation, shedding their original informational functions to acquire fresh artistic significance. Take, for instance, the conversion of stock market data, initially utilitarian for traders, into sonified representations for artistic expression, thereby providing a reinterpretation of the data while acknowledging their informational origins.

To dissect the creative process in sonification art, Mazzola[330] proposes a structured framework comprising seven sequential stages. The artist progresses through these steps, continually refining their artistic endeavor:

1. Posing an Initial Inquiry: Commencing the creative journey by delineating the subject of exploration.
2. Grasping the Context: Acknowledging that the initial inquiry is situated within a broader context and seeking contextual clues to address it.

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[329] Danto, 1998.

[330] Mazzola et al., 2011.

3. Identifying the Core Concept: Pinpointing the fundamental idea or pivotal symbol within this contextual framework.
4. Recognizing Constraints: Comprehending the factors that confine or delineate this core concept.
5. Challenging Boundaries: Questioning the necessity of these limitations and seeking alternative perspectives.
6. Exploring Novel Viewpoints: Examining the alternative perspectives identified in the previous step and evaluating their integration into the artistic work.
7. Evaluating Emerging Concepts: Assessing whether the new perspectives effectively enrich the core concept. If not, revisiting earlier stages to delve deeper, uncovering fresh constraints and expansions, or even identifying a new central concept.

These procedures can be divided into two main phases: steps 1-4 focus on the initial conceptualization stage, while steps 5-7 are oriented towards broadening the scope of the endeavor.[331]

The relevance of Mazzola et al.'s framework of seven steps to the evaluation of sonification art requires careful consideration; *can this approach be effectively applied to the analysis of sonification art?* Before delving into this inquiry, let's explore several examples of sonification art to provide context for the practice.

4.2.7: Aesthetic Framework for Sonification Art

The discussed artworks emphasize the importance of sound in creating aesthetic experiences, diverging from the scientific approach of sonification where the primary goal is to render data understandable. In artistic practices, this objective may even be entirely absent. Roden and Polsenberg reflect on their installation piece, *Ear(th)*:

> Just as the installation would look and sound different if the data source was the ocean or Shakespeare; Ear(th) in no way attempts to illustrate the earth's movement or to recreate an

[331] Van Ransbeeck, 2018.

> earthquake experience through sound. I am much more interested in simply allowing the earthquake data to generate a sound composition and to allow for my own misreadings of the data to suggest placements, sound ideas, performances, and sculptural forms. For me, this process is a kind of alchemy—to allow the materials to be transformed into something completely connected to, yet seemingly distant from, the source.[332]

The artwork assigns a distinct meaning to the data, introducing an extra level of interpretation. The artist transforms the original purpose of the data, utilizing its value to underscore a musical element. Unlike in scientific sonification, where impartiality is key, in sonification art, the priority is to convey the artist's intended message or aesthetic experience.

4.2.7.1: Sonification in an Artistic Context

Earlier, we discussed Mazzola et al.'s seven-step process, and now we want to apply these divisions to sonification art.

In the first step, we question whether a dataset can inspire compelling music. For this, we require a method to translate data into sound, with data serving as the work's foundation.

We then examine the boundaries of the concept within its specific setting. The dataset could lack interest, or the methods of translation may fail to generate compelling music. In such instances, the artist might opt to amend the dataset or adjust the musical interpretation using alternative methods. For example, seismic data characterized by frequent activity might offer more intrigue compared to a period of relative calm. Altering the dataset leads to diverse outcomes. Alternatively, if the artist is satisfied with the dataset, they can refine the musical rendition instead. These iterative adjustments yield deeper insights, ultimately culminating in the intended artistic expression.

Sonification art often undergoes an iterative and gradual refinement process. The emphasis lies not solely on the final outcome but also on its integration within a design framework. The

---

[332] Roden & Polsenberg, 2004.

composition evolves into a systematic design, with the musical piece serving as an embodiment of this design. There are distinct stages in this process where adjustments can be implemented:

1. Data Selection: The selection of diverse data holds paramount importance. If the dataset lacks variety, the artist might opt to change it.
2. Data Mapping: Experimentation with various mapping techniques is instrumental in discovering the most captivating approach.
3. Sound Artifact: Even following the design phase, the sound may not meet the artist's expectations. In such cases, the artist can either accept it as a natural consequence or proceed with adjustments accordingly.

Every alteration signifies a stride in the gradual evolution of the desired creation. This advancement doesn't strictly adhere to a linear path; artists may adjust the correlations, subsequently discover the data lacking engagement, and then reassess the correlations using an alternative dataset or change the mapping strategies.

Integrating non-musical elements, such as data, into musical compositions can spark novel artistic expressions. Utilizing non-musical data in musical contexts does not always lead to conventional musical structures, whether in terms of melody, rhythm, or other musical parameters. However, this does not signify a lack of quality in the resulting music; rather, techniques like sonification can reveal distinctive musical structures. Doornbusch highlights in the context of algorithmic composition, applicable to sonification, that "Working with computers in this manner has prompted me to conceive compositional ideas that would not have arisen otherwise."[333] These insights nurture innovative compositions, demonstrating a novel approach to artistic creation. Consequently, it can be inferred that sonification can serve as a method of creating new musical pieces by transforming and repurposing data.

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[333] Doornbusch, 2005.

4.3: Sonification Art Portfolio

The concluding part of this chapter highlights the associated sound arts portfolio, which employs sonification as its primary compositional method.

4.3.1: The Artist and the Element

As a sound artist, I view sonification as a method for creating sound in order to discern patterns, and gain a new perspective on a particular data set. As discussed in earlier chapters, sonification originates from scientific research and offers an alternative approach to understanding data trends. Data typically possess their own inherent integrity, and transforming data into sound is a secondary objective. Nevertheless, when such data utilized by a sound artist, sonification can introduce a scientifically informed aspect to an artistic work.

Understanding the methodology employed and discerning the nature and origin of the data is frequently imperative for a thorough comprehension of such a piece. However, it is not always necessary to be familiar with the processes of sonification (for example, an artist's approaches to parameter mapping) in order to derive enjoyment from the final product—each piece discussed in this section can be valued solely for its experiential qualities without knowing exactly how it was produced. The narrative surrounding a specific sonification, rather than the methodology, can enhance the comprehension of a piece and elucidates the artist's inspiration.

As mentioned, I believe that sonification is the result of deliberate choices made by the sound artist. Given that there are numerous alternatives for generating audio content—many of which are less complex than sonification—I opt for sonification when I want to bring an aspect of scientific methodology to my art. I am intrigued by the concept of using sound to represent naturally occurring phenomena. Consequently, my approach to various sonification tasks ranges from exploring simple auditory curiosity to incorporating elements of scientific methodology into the core of a project. Consequently, in some instances, the process of sonification itself becomes the main driving force and source of inspiration for creating a piece of sound art.

From a scientific perspective, sonification serves as a valuable tool for comprehending data patterns or phenomena. Through repetition, looping, and the interpretation of auditory representations generated from data sets, significant insights can be gleaned regarding the underlying information source. In such contexts, the function of the data shifts to that of imparting organization, reminiscent of the vast cosmos rather than a conventional musical score. This concept offers the potential for the creation of conceptual compositions rooted in empirical observations. This aspect of working with empirical data through the process of sonification is specifically attractive to me.

Sonification offers a means to uncover hidden data structures and nuanced trends beyond the straightforward analysis and visualization of numerical data. Its outcomes diverge from purpose-driven compositions, aligning instead with the intrinsic characteristics of the data itself. Unlike conventional linear temporal progressions in composed music, *sonification introduces an organic, dynamic unity, emphasizing vertical auditory interactions over the typical horizontal unfolding found in traditional musical compositions*. This has strongly influenced my interest for signification art.

4.3.2: Listening to Data: A Collection of Creative Sonification

"Listening to Data" (2023) presents a series of audiovisual compositions that delve into the intriguing practice of sonification, transforming datasets and abstract visuals into auditory experiences accompanied by visual imagery, thereby creating an immersive encounter for viewers. Each composition draws from a diverse array of scientific data, spanning from variations in the COVID-19 virus to the expansive depths of our galaxy, to craft a varied sonic landscape. Utilizing a rich spectrum of sound, these compositions encapsulate the essence of the data, offering a dynamic and immersive audiovisual journey that encourages exploration of the intricate facets of our world through sound and image. This collection serves as a testament to the creative potential of sonification, inviting audiences to discover the concealed beauty and complexity of our reality through the prism of data.[334]

4.3.2.1: Compositions in this collection ~ 30 minutes

This collection consists of three audiovisual works that use different datasets to create sonification art.

The Killer Data ~ 11:11

This piece explores the genetic mutations of the COVID-19 virus observed during the pandemic, illustrating a multifaceted sonic composition that mirrors both the alterations in the virus's genetic structure and the correlated mortality rates, alongside the overarching emotional and psychological ramifications of the pandemic on communities. In the creation of this composition, I utilize mortality statistics from diverse regions, converting them into auditory patterns employing a customized sonification algorithm. The resultant sonified sound undergoes additional modification and, paired with artistic visual interpretations of data, adapts to the evolving auditory dynamics, thus crafting an immersive audio-visual presentation.

The Galaxy ~ 04:02

This composition comprises three movements and draws upon diverse astronomical data to construct an auditory ambiance reflective of the mysterious essence of celestial entities. Through its three movements, the composition endeavors to immerse the audience in a transcendent voyage across the cosmos, eliciting awe and curiosity towards the enigmatic wonders of the universe.

Distorted Imagery ~ 07:42

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[334] The collection was exhibited at the Digital Scholarship Centre, University of Alberta, 13&14 April 2023. And at the Gallery of Sound Studies Institute, University of Alberta, Oct 10 - Nov 2, 2023.

The concluding addition to this compilation delves deeper into the technique of sonification, utilizing geometric multicolor patterns as the foundational dataset. By meticulously examining the visual information available, I employ diverse methodologies to craft an immersive audiovisual presentation. The resultant creation signifies a daring and innovative extension of the sonification approach, pushing its boundaries into novel and stimulating domains of artistic interpretation.[335]

4.3.3: Mapping: Coding

In this section, I aim to present an elementary illustration of parameter mapping sonification, wherein discrete data points are translated into musical notes. This can be conceptualized as a musical rendition of a scatter plot,[336] with temporal progression represented along the x-axis and musical pitch along the y-axis. Although this method may be particularly intuitive when employed with time series data, given the inherent temporal association with the x-axis, its applicability extends to diverse datasets irrespective of the variables represented on each axis.

As an illustration, I will replicate a modified version of the sonification technique employed

lunarCraterAges

names	longitude	latitude	diameter	age
Copernicus	339.92969	9.6328	96.7	797
Tycho	348.71469	-43.2589	85.7	85
King	120.4922	4.9375	76.2	992
Jackson	196.6895	22.04	71.4	147
Ohm	246.27397	18.28491	64.3	291
Anaxagoras	349.84981	73.47243	52.9	586
Crookes	194.91659	-10.38596	51.5	446
Glushko	282.30728	8.14047	43.1	196
Aristarchus	312.50781	23.7422	40	164
Necho	123.2461	-5.2266	36.8	80
Das	222.95444	-26.50499	36.4	657
Petavius B	57.03722	-19.93235	34.4	224
Thales	50.30963	61.70299	31.8	61
Kepler	321.99111	8.11741	31.5	930
Proclus	46.893	16.066	28.2	254
Lalande	351.37109	-4.4668	23.7	495
Moore F	185.03419	37.2864	23.6	41
Larmor Q	176.32069	28.6689	23.1	178
Giordano Bruno	102.8675	35.9665	22.1	4
Schwabe F	50.15153	66.42775	21.4	814
Innes G	122.4312	26.8637	21.1	527

[335] Mapping in Image Sonification is illustrated in section “4.3.4.2: Sonify Image: Mapping”

[336] A scatter plot is a type of data visualization that represents individual data points in a two-dimensional space, where each axis corresponds to one of the variables being analyzed. The position of each point on the horizontal (x) axis and vertical (y) axis indicates the values of the two variables, allowing for the visualization of patterns, correlations, and distributions within the data set.

in the composition titled "The Galaxy". The process will commence with the compilation of a roster featuring lunar impact craters exceeding a diameter of 10km and possessing age approximations. This dataset is derived from a study authored by Sara Mazrouei,[337] wherein she identified a notable surge in the rate of impacts around 290 million years ago. Employing sonification, I aim to audibly perceive the temporal pattern of these substantial impacts spanning the past billion years. The transformation of crater diameters into pitch and velocity parameters will enable the auditory representation of the distribution of impact magnitudes throughout the temporal continuum.

The output will be a MIDI file (.mid) which can be opened in any DAW (digital audio workstation) where I will be able to choose any instrument or sound I want. The code, in Python, is presented in many small steps with figures to be more accessible to beginners. While it is certainly possible to use data to control a much wider range of audio and musical parameters beyond pitch and velocity, I will keep this coding at a basic level to ensure the discussion on mapping remains simple and clear.

Steps:

1) Importing data.csv:

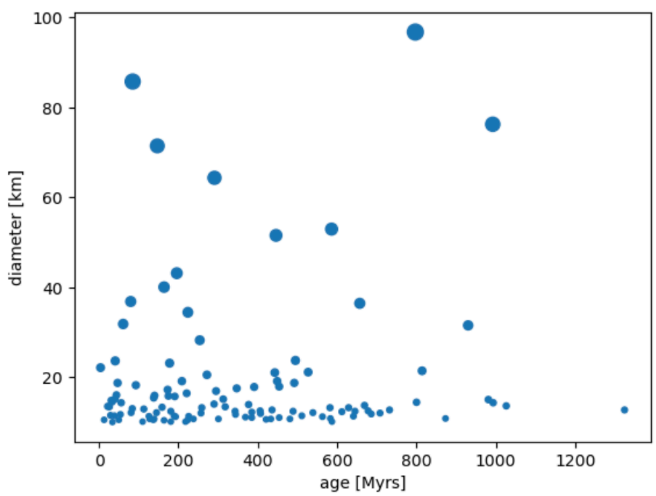
```
import pandas as pd   #import library for loading data, https://pypi.org/project/pandas/

filename = 'lunarCraterAges'  #name of csv data file

df = pd.read_csv('./data/' + filename + '.csv')  #load data as a pandas dataframe
#df = df[(df['diameter'] >= 20)] #filter data if you like (for example, only craters larger than 20km)

df = df.sort_values(by=['age'], ascending=False) #sort data from oldest to youngest
                                                 #(this is optional, doesn't affect the sonification)

n_impacts = len(df)
print(n_impacts, 'impacts')

df.head() #take a look at first 5 rows
#df.tail() #take a look at last 5 rows
```

```
111 impacts
```

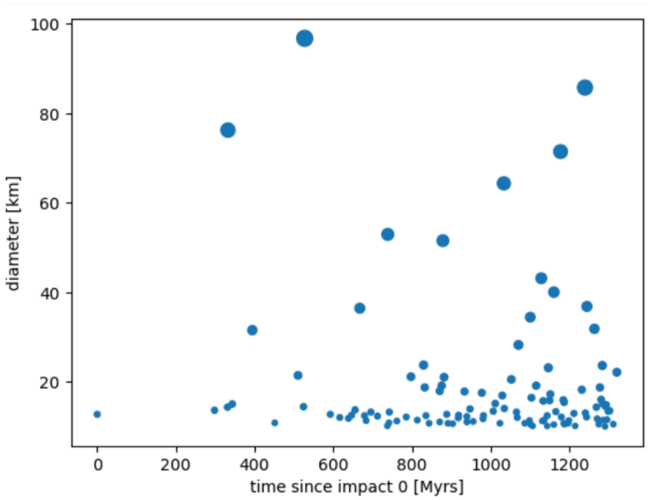
	names	longitude	latitude	diameter	age
60	Mosting A	354.80469	-3.22070	12.7	1324
50	NaN	262.67029	43.65850	13.6	1026
45	NaN	79.73330	22.83180	14.3	993
2	King	120.49220	4.93750	76.2	992
41	Hume Z	90.41211	-3.62497	15.0	981

2. Plotting:

```
import matplotlib.pylab as plt  #import library for plotting

ages = df['age'].values    #numpy array, to do mathematical operations directly on the object
diameters = df['diameter'].values

plt.scatter(ages, diameters, s=diameters)
plt.xlabel('age [Myrs]')
plt.ylabel('diameter [km]')
plt.show()
```




```
times_myrs = max(ages) - ages  #measure time from oldest crater to youngest in data

plt.scatter(times_myrs, diameters, s=diameters)
plt.xlabel('time since impact 0 [Myrs]')
plt.ylabel('diameter [km]')
plt.show()
```



3. Mapping:

Below are some code examples of how I map elements of data to sound characteristics. For example, here I calculate the total number of beats in a time span, assuming 25 million years per beat:

```
def map_value(value, min_value, max_value, min_result, max_result):

    result = min_result + (value - min_value)/(max_value - min_value)*(max_result - min_result)
    return result
```

```
#compressing time
myrs_per_beat = 25  #number of million of years for each beat of music (in MIDI)

t_data = times_myrs/myrs_per_beat #rescale time from Myrs to beats

t_data  # 1 beat = 1 quarter note
```

```
array([ 0.  , 11.92, 13.24, 13.28, 13.72, 15.76, 18.04, 20.4 , 20.96,
       21.08, 23.68, 24.64, 25.52, 25.84, 26.2 , 26.68, 27.16, 27.32,
       27.8 , 28.48, 29.48, 29.52, 29.64, 29.68, 30.44, 31.4 , 31.88,
       32.52, 33.16, 33.28, 33.4 , 33.72, 34.8 , 34.8 , 35.  , 35.12,
       35.24, 35.52, 35.64, 36.12, 36.68, 36.72, 37.32, 37.56, 37.56,
       37.88, 38.2 , 39.08, 39.2 , 39.24, 40.24, 40.44, 40.92, 41.16,
       41.32, 41.36, 42.08, 42.6 , 42.68, 42.8 , 43.44, 43.92, 44.  ,
       44.04, 44.12, 44.24, 44.6 , 45.12, 45.24, 45.32, 45.4 , 45.72,
       45.72, 45.84, 45.96, 46.04, 46.4 , 46.4 , 46.6 , 47.08, 47.16,
       47.36, 47.4 , 47.44, 47.48, 47.84, 47.92, 48.44, 48.56, 49.24,
       49.56, 49.6 , 49.72, 49.76, 50.52, 50.72, 50.8 , 50.96, 51.08,
       51.2 , 51.32, 51.36, 51.4 , 51.6 , 51.64, 51.72, 51.8 , 51.92,
       52.08, 52.44, 52.8 ])
```

```
myrs_per_beat = 25 # 25 million years per beat

t_data = times_myrs/myrs_per_beat

duration_beats = max(t_data)  #duration in beats (beats of the last note)
print('Duration:', duration_beats, 'beats')
```

```
Duration: 52.8 beats
```

Given the dataset, we can confirm how many millions of years are represented by one musical beat:

```
duration_beats = 52.8 #desired duration in beats (beats of last note)

t_data = map_value(times_myrs, 0, max(times_myrs), 0, duration_beats)

t_data
```

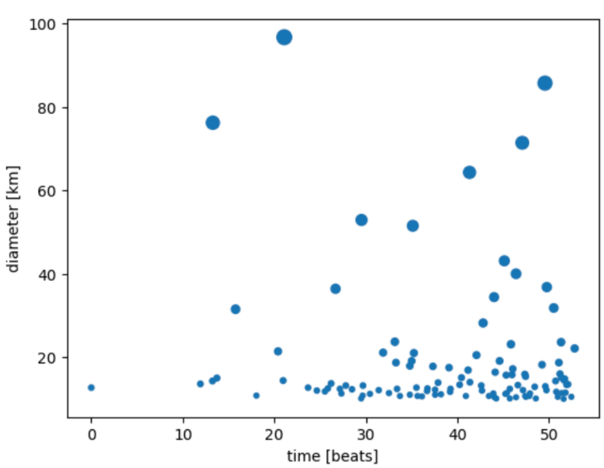
```
array([ 0.  , 11.92, 13.24, 13.28, 13.72, 15.76, 18.04, 20.4 , 20.96,
       21.08, 23.68, 24.64, 25.52, 25.84, 26.2 , 26.68, 27.16, 27.32,
       27.8 , 28.48, 29.48, 29.52, 29.64, 29.68, 30.44, 31.4 , 31.88,
       32.52, 33.16, 33.28, 33.4 , 33.72, 34.8 , 34.8 , 35.  , 35.12,
       35.24, 35.52, 35.64, 36.12, 36.68, 36.72, 37.32, 37.56, 37.56,
       37.88, 38.2 , 39.08, 39.2 , 39.24, 40.24, 40.44, 40.92, 41.16,
       41.32, 41.36, 42.08, 42.6 , 42.68, 42.8 , 43.44, 43.92, 44.  ,
       44.04, 44.12, 44.24, 44.6 , 45.12, 45.24, 45.32, 45.4 , 45.72,
       45.72, 45.84, 45.96, 46.04, 46.4 , 46.4 , 46.6 , 47.08, 47.16,
       47.36, 47.4 , 47.44, 47.48, 47.84, 47.92, 48.44, 48.56, 49.24,
       49.56, 49.6 , 49.72, 49.76, 50.52, 50.72, 50.8 , 50.96, 51.08,
       51.2 , 51.32, 51.36, 51.4 , 51.6 , 51.64, 51.72, 51.8 , 51.92,
       52.08, 52.44, 52.8 ])
```

```
#t_data = map_value(ages, min(ages), max(ages), duration_beats, 0)

myrs_per_beat = max(times_myrs)/duration_beats
print('Myrs per beat:', myrs_per_beat)
```

```
Myrs per beat: 25.0
```

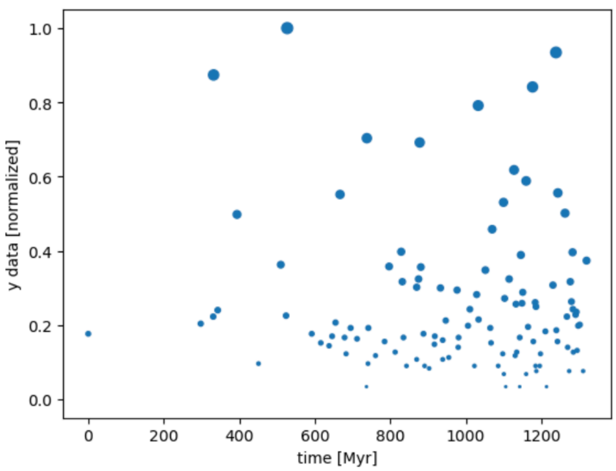
```
# duration in seconds (calculating Tempo)
bpm = 60  #if bpm = 60, 1 beat = 1 sec (bpm = beats per minute)
duration_sec = duration_beats*60/bpm #duration in seconds (of the last note)
print('Duration:', duration_sec, 'seconds')


plt.scatter(t_data, diameters, s=diameters)
plt.xlabel('time [beats]')
plt.ylabel('diameter [km]')
plt.show()
```

```
Duration: 52.8 seconds
```



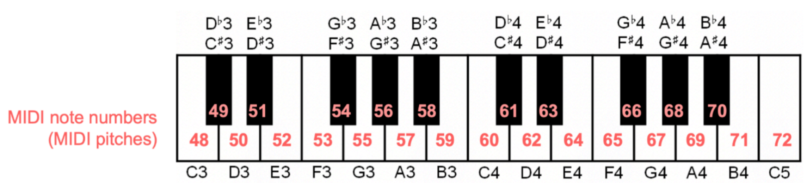
4. Normalize & Scale Data:

```
y_data = map_value(diameters, min(diameters), max(diameters), 0, 1) #normalize data, so it runs from 0 to 1

y_scale = 0.5  #define scaling parameter, lower than 1 to spread out more evenly

y_data = y_data**y_scale

plt.scatter(times_myrs, y_data, s=50*y_data)
plt.xlabel('time [Myr]')
plt.ylabel('y data [normalized]')
plt.show()
```



5. Pitch Mapping, Choosing Musical Notes:

In the process of MIDI (Musical Instrument Digital Interface) conversion, there is a common practice of selecting a specific range of musical notes to correspond with data, often encompassing several octaves of a particular scale. However, it is also feasible to opt for any custom selection of notes, contingent upon the intended objectives for the sonification process. The overall quantity of notes chosen determines the pitch resolution, akin to the number of rows in an image; these note designations are then translated into MIDI note numbers, represented as integers ranging from 0 to 127. For instance, on a piano, the lowest note A0 corresponds to 21, while C1 equals 24, and so forth.

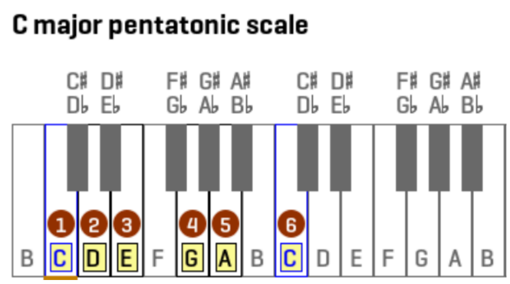


```python
#string to midi, from audiolazy library to convert between notes and midi numbers
#midi numbers are integers

from audiolazy import str2midi

# 4 octaves of C major scale (#later check minor scale and no scale!)
note_names = ['C2','D2','E2','F2','G2','A2','B2',
              'C3','D3','E3','F3','G3','A3','B3',
              'C4','D4','E4','F4','G4','A4','B4',
              'C5','D5','E5','F5','G5','A5','B5']

#for every note name in the "note_names" list,run this function to find the corresponding midi number
note_midis = [str2midi(n) for n in note_names]

note_midis
```

The output of the above code is a list of midi notes as represented by numbers: [36, 38, 40, 41, 43, 45, 47, 48, 50, 52, 53, 55, 57, 59, 60, 62, 64, 65, 67, 69, 71, 72, 74, 76, 77,79, 81, 83]

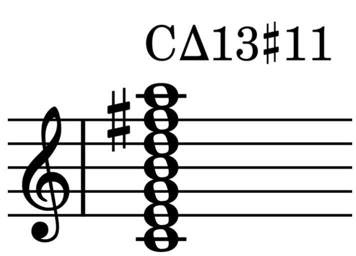
For example, if I choose to map onto the C major pentatonic scale, I use the Python function *str2midi()* to correlate data to MIDI numbers:

```python
#4 octaves of major pentatonic scale
note_names = ['C2','D2','E2','G2','A2',
              'C3','D3','E3','G3','A3',
              'C4','D4','E4','G4','A4',
              'C5','D5','E5','G5','A5']

note_midis = [str2midi(n) for n in note_names]

note_midis
```



Output: [36, 38, 40, 43, 45, 48, 50, 52, 55, 57, 60, 62, 64, 67, 69, 72, 74, 76, 79, 81]

Or, Cmaj13#11 chord, C lydian…



```python
#custom note set (a voicing of a Cmaj13#11 chord, notes from C lydian)
note_names = ['C1','C2','G2',
              'C3','E3','G3','A3','B3',
              'D4','E4','G4','A4','B4',
              'D5','E5','G5','A5','B5',
              'D6','E6','F#6','G6','A6']

note_midis = [str2midi(n) for n in note_names]

note_midis
```

Output: [24, 36, 43,48,52, 55, 57, 59, 62, 64, 67, 69, 71, 74, 76, 79, 81, 83, 86, 88, 90, 91, 93]

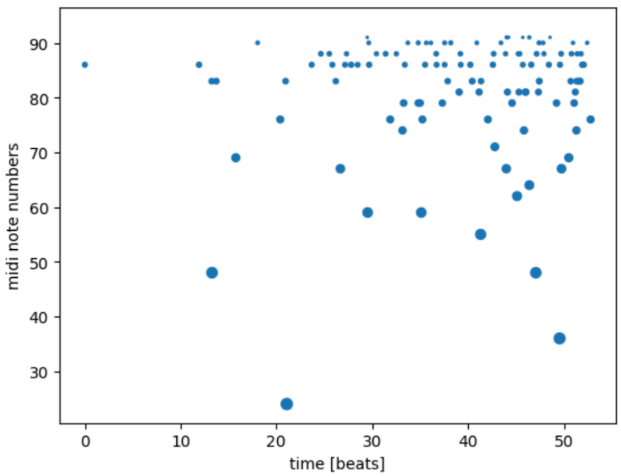
```python
note_names = ['C1','C2','G2',
              'C3','E3','G3','A3','B3',
              'D4','E4','G4','A4','B4',
              'D5','E5','G5','A5','B5',
              'D6','E6','F#6','G6','A6']

n_notes = len(note_midis)
print('Resolution:',n_notes, 'notes')
```

```
Resolution: 23 notes
```

6. Mapping Data to MIDI Numbers (Pitches)

Here, I make a choice about polarity: bigger craters in the data are mapped to lower notes. I round the results because midi notes have to be integers but *map_value()* returns a decimal:

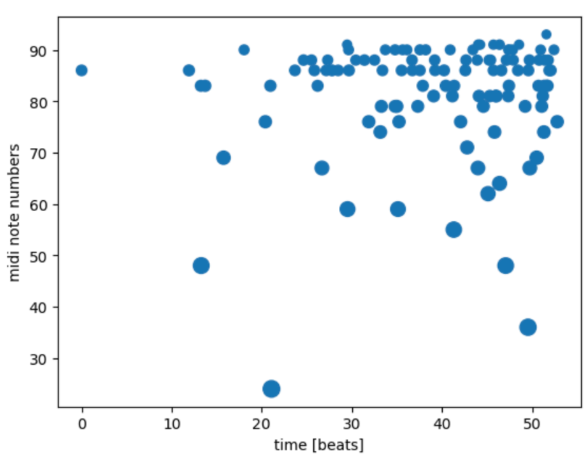
```python
midi_data = [] #defining midi data into a list

for i in range(n_impacts):

    note_index = round(map_value(y_data[i], 0, 1, n_notes-1, 0))
    #choice of polarity: bigger craters (data) are mapped to lower notes
    #we round the results because note midi have to be integer but map_value will return decimal

    midi_data.append(note_midis[note_index])

plt.scatter(t_data, midi_data, s=50*y_data)
plt.xlabel('time [beats]')
plt.ylabel('midi note numbers')
plt.show()
```



7. Map Data to Note Velocities (Larger Craters/Data to Bigger Velocities)

The MIDI velocity (an integer from 0-127) is a combination of volume and intensity.[338] I am using the same data to control the note velocity too. First I define *minimum* and *maximum* velocity and other notes are then "normalized" into that range.

```
#minimum and maximum note velocity, 0 will be hard to hear so I start from 35
vel_min,vel_max = 35,127

vel_data = []
for i in range(n_impacts):
    note_velocity = round(map_value(y_data[i], 0, 1, vel_min, vel_max))
    #bigger craters will be louder, round here again because note velocites are also integers
    vel_data.append(note_velocity)

plt.scatter(t_data, midi_data, s=vel_data) #controling size of the dots with vel
plt.xlabel('time [beats]')
plt.ylabel('midi note numbers')
plt.show()
```



[338] For example, hitting a piano key with a larger velocity makes a louder, more intense sound.

8. Saving Data as MIDI file

A MIDI file will be created that can be imported into any DAW (Digital Audio Workstation) like Logic, Garageband, Ableton, ProTools, etc.

```
#import library to make midi file
from midiutil import MIDIFile

#create midi file object, add tempo
my_midi_file = MIDIFile(1)
my_midi_file.addTempo(track=0, time=0, tempo=bpm) #there is only one track, bpm is 60

#add midi notes
for i in range(n_impacts):
    my_midi_file.addNote(track=0, channel=0, pitch=midi_data[i], time=t_data[i], duration=2, volume=vel_data[i])

#create and save the midi file itself
with open(filename + '.mid', "wb") as f:
    my_midi_file.writeFile(f)
```

4.3.4: Image Sonification: Yeg|Scaping

4.3.4.1: Yeg|Scaping ~ 45 minutes[339]

Drawing inspiration from the concept of 'soundscape' as introduced by Raymond Murray Schafer, "Yeg |Scaping" (2023) reimagines the auditory dimensions of landscapes through the lens of visual imagery. Departing from traditional analyses centered on the

Kinnard Park, Edmonton, AB. Photo Credit: Nina Ghayem

[339] Audiovisual Performance of Image Sonification in the form of an Installation, live Performance & Visuals. This work was performed on September 22, 2023, at Fine Arts Building, Studio 2-7, University of Alberta. Event was coordinated by Sound Studies Institute, UofA.

sonic characteristics of a specific locale, the work initiates its exploration from a photographic depiction of a real landscape, which is subsequently transformed into sound via image sonification techniques.[340] Going beyond mere static representation, both visually and sonically, the sounds are dynamically reorganized and manipulated in real-time (utilizing methods such as spectral processing and granular synthesis), and then reintegrated into the original image, thereby distorting, altering, and reshaping the landscape into novel forms. By selecting a photograph captured in Edmonton, Alberta, where the collaborators were situated during the creation process, the intent was to convey a personalized and fresh interpretation of their urban experience..

4.3.4.2: Sonify Image: Mapping

In order to harness visual data for musical applications, it is crucial to comprehend and acknowledge the inherent temporal characteristics of sound. Time serves as the primary framework within which all auditory elements are situated, presenting a unique hurdle in effectively translating time-agnostic visual content into music through sonification techniques and their practical implementations.

Because of its inherent reliance on time, the representation of data in the auditory realm necessitates addressing temporal organization. Within auditory display research, time is not merely a variable; rather, it serves as the primary dimension for positioning all other auditory parameters. While the temporal sequencing of information presents minimal challenges, it significantly impacts the sonification process of static data like images devoid of inherent temporal structure. Consequently, an intentional temporal mapping is essential, one not arbitrarily aligned with a linear left-to-right scan.

Another crucial aspect contributing to the process of image sonification pertains to its geometric attributes. A static visual representation operates within a two-dimensional framework, where

[340] This audiovisual performance is a collaboration by Nina Ghayem and Rémy Bocquillon. The image sonification for this piece was done entirely by Ghayem.

individual pixels can be assigned varying sets of color values, typically in the form of three (RGB) or four (RGBA, or CMYK) components. This intricate two-dimensional structure enables the establishment of diverse reference markers for pinpointing the dataset intended for sonification.

Below is an illustrative Python code excerpt aimed at image sonification, showcasing the process of generating a soundscape from an image. It showcases the utilization of various functions and entails loading a jpg image, scanning it sequentially from left to right. The mapping of pixels to notes follows specific rules: the left-to-right column position corresponds to time, the luminosity (pixel brightness) determines the pitch within a defined scale, the redness (pixel R value) dictates the duration, while the blueness (pixel B value) regulates the volume.

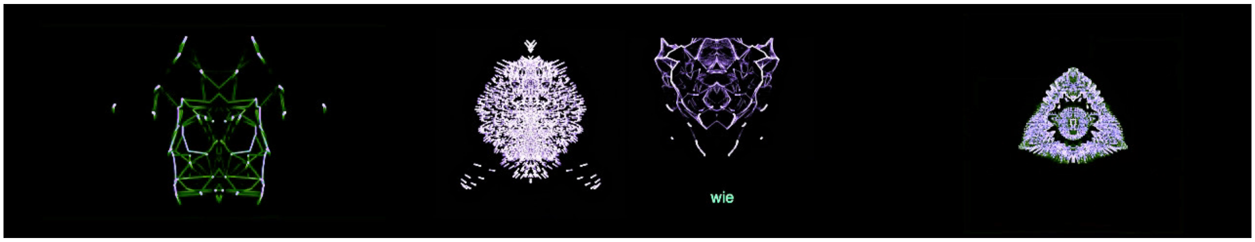
```
from music import *
from image import *
from random import *

##### define data structure
soundscapeScore = Score("Thisss", 60)
soundscapePart  = Part(PIANO, 0)

##### define  musical parameters
scale = MIXOLYDIAN_SCALE

minPitch = 0        # MIDI pitch (0-127)
maxPitch = 127

minDuration = 0.8   # duration (1.0 is QN)
maxDuration = 6.0

minVolume = 0       # MIDI velocity (0-127)
maxVolume = 127

# start time is randomly displaced by one of thi
# durations (for variety)
timeDisplacement = [DEN, EN, SN, TN]

##### read in image (origin (0, 0) is at top le
image = Image("Thisss.jpeg")
```

1

```
# specify image pixel rows to sonify - this depends on the image!
pixelRows = [0, 53, 106, 159, 212]
width = image.getWidth()     # get number of columns in image
height = image.getHeight()   # get number of rows in image

##### define function to sonify one pixel
# Returns a note from sonifying the RGB values of 'pixel'.
def sonifyPixel(pixel):

   red, green, blue = pixel  # get pixel RGB value

   luminosity = (red + green + blue) / 3   # calculate brightness

   # map luminosity to pitch (the brighter the pixel, the higher
   # the pitch) using specified scale
   pitch = mapScale(luminosity, 0, 255, minPitch, maxPitch, scale)

   # map red value to duration (the redder the pixel, the longer
   # the note)
   duration = mapValue(red, 0, 255, minDuration, maxDuration)

   # map blue value to dynamic (the bluer the pixel, the louder
   # the note)
   dynamic = mapValue(blue, 0, 255, minVolume, maxVolume)

   # create note and return it to caller
   note = Note(pitch, duration, dynamic)

   # done sonifying this pixel, so return result
   return note
```

2

4.3.5:This is aRt[341]



4.3.5.1: Project Description

“This is aRt” (2023) sits at the intersection of technology, data science and art. In this project, I combine data sonification and visualization techniques to create an art installation. The piece showcases dynamic visual elements that represent data patterns through evolving shapes and textures. Simultaneously, these visuals trigger a dynamic soundscape, where data attributes are transformed into musical elements, rhythms, and tones, offering the audience a constantly changing audiovisual experience. By merging data visualization and sonification, I explore data in a multisensory way, providing a comprehensive perspective on the data's underlying meaning and aesthetics. This fusion of visual and auditory elements aims to bridge the gap between data science and artistic expression, offering a unique and thought-provoking encounter.

4.3.5.2: Technical Aspects

Why “aRt” in the title?

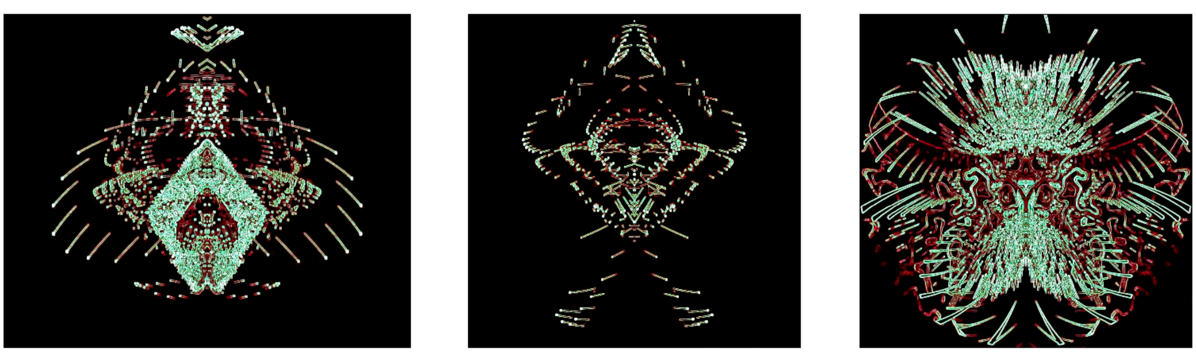
“aRt” is no typo, it is a playful reference to the "aRt" library in the computer programming language, “R”, which serves as a crucial tool in my creative process. In programming, a "library" is a collection of pre-written code, functions, and routines that simplify complicated computing tasks. For this project, I utilized the "aRt" library, along with “aRtsy” and the R package

341 This Media Art Installation was exhibited from Nov 27 to Dec 1st, 2024, at the Visualization Room, Digital Scholarship Centre, University of Alberta.

"generativeart," to facilitate innovative data visualization. Beyond its technical aspects, the project's title deliberately emphasizes its nature as a multidisciplinary research-creation initiative rather than strictly scientific research. This designation signifies a blend of academic research and creative exploration. "This is aRt" seeks to break down barriers between traditional scientific inquiry and artistic expression, positioning itself as an artwork. Through an interdisciplinary approach, the project seeks to engage audiences beyond scientific exploration, inviting them to appreciate the artistic dimensions within the data.

What do I mean by data visualization?

When I talk about the concept of data visualization in the form of art, I am essentially taking the raw and often complex information found in a dataset and transforming it into visually expressive artwork. In this context, I might employ a variety of visual elements such as colours, shapes, patterns, and overall design principles to communicate different aspects of the data. The goal for me is not just to present information and hidden patterns found in the dataset, but to do so in a way that engages the viewer aesthetically, inviting them to explore, and interpret the data on a more visceral level. It's a way of making the data not just something to be understood but something to be felt—an experience that combines both the analytical and emotional aspects of engaging with information.

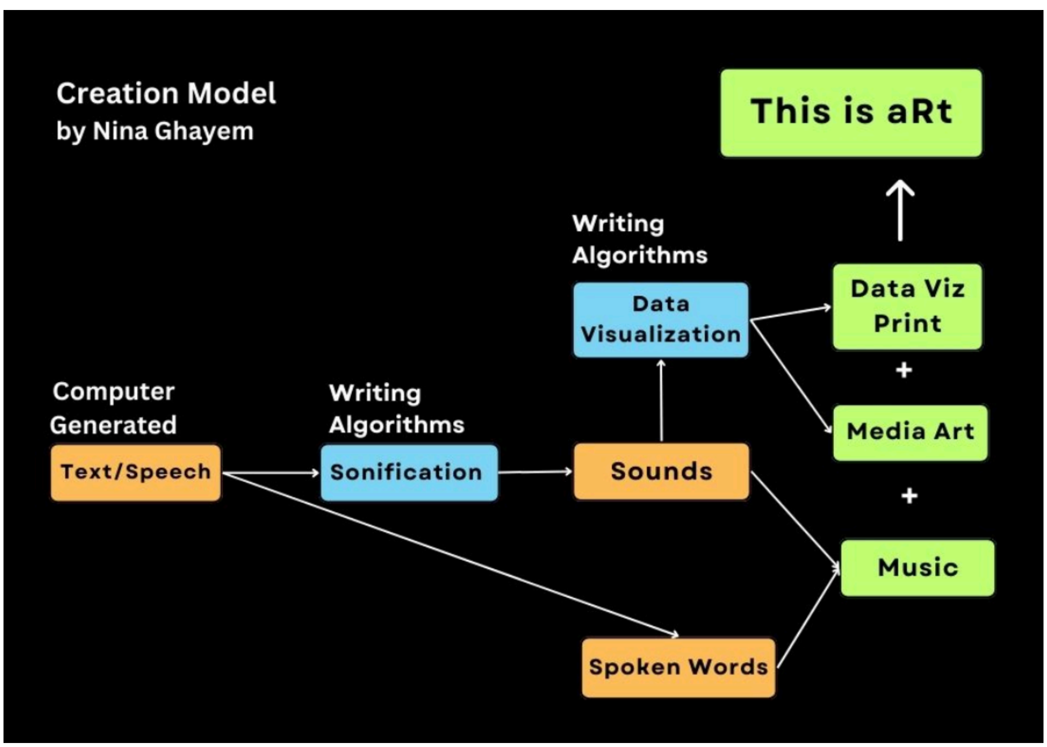


A few visualizations of textual data created in "this is aRt" project

What do I mean by data sonification?

When I talk about data sonification in the form of art, I'm describing a creative process that uses sound to bring data to life. It's like turning numbers and information into a musical composition or an auditory experience, creating a data-driven artwork that you can listen to. In this approach, data isn't just visually represented; it takes on a new life through soundscapes, rhythms, and timbre. I use different audio elements to convey various aspects of data. The aim isn't solely to communicate information but also to immerse the audience in a unique and aesthetic auditory experience. Sonification transforms data into a sensory experience, allowing you to "hear" and interpret information in a way that goes beyond traditional visual representations. Similar to composing music, data sonification as art seeks to evoke emotions, prompt reflection, and provide a vision of the presented information.

4.3.6: Creation Model: Methodology



This chart illustrates the sequential process I followed to create this installation.

Steps: The creation model for this project follows 6 main steps as follow:

1. Designing algorithms and coding for text generation:

In the initial step, I engaged in the conceptualization and design of algorithms to generate text. These algorithms outlined the logical steps and rules for text generation, considering factors such as the arrangement of letters, words, and phrases (structure), and the intended meaning or content conveyed by the text. Subsequently, I transitioned to writing code, translating this set of rules into a specific programming language like Python and R. The code serves as the concrete implementation of the designed algorithms, bringing the conceptualized text generation process to life.

2. Sonifying text and mapping elements to sound:

With the generated text in place, the next step involves sonification—transforming the text into sound. Here, I designed a set of algorithms to map elements of the text to corresponding elements of sound, considering aspects such as pitch, rhythm, and intensity. These algorithms guide the creation of sonified sounds with a specific emphasis on aesthetic considerations. Subsequently, I wrote code to implement these designed algorithms using the Python programming language.

3. Turning text into speech:

Simultaneously with the sonification process, I design algorithms specifically tailored to convert the textual content into synthetic speech or spoken words. This parallel process contributes to the audio diversity of the project, introducing a synthetic voice component alongside the sonified sounds. Again, I translate these designed algorithms into code, providing the concrete implementation of the text-to-speech transformation.

4. Data visualization in the R programming language:

The sonified sounds, now represented as audio data, undergo the process of data visualization. Utilizing the R programming language, I designed a set of algorithms for creative data visualization, that guide the creation of diverse visualizations. Subsequently, I wrote code to implement these algorithms, producing thousands of images that capture various representations of the sonified data.

5. Transforming images into dynamic videos:

The exported images from the data visualization phase are transformed into dynamic videos. I used specialized programs such as Adobe After Effects and Premiere Pro in combination with coding. I introduced movements, occasionally synchronizing specific visual elements with layers of sounds for a cohesive experience. However, intentional desynchronization is also employed in certain instances to create diverse and dynamic interactions between the visuals and different layers of auditory elements.

6. Composing music from multiple layers of sonified sounds:

The final step involves composing the musical component of the installation. Here, music consists of multiple layers of rhythmic, melodic, and ambient sounds, in addition to the spoken words—each representing different results of the sonification process. I bring these auditory elements together, using compositional techniques to create a cohesive and expressive musical composition.

4.3.7: Textual Data: Concept

In this project, I utilize textual data as the primary input for the processes of sonification and data visualization. The text itself is generated through custom coding in Python, taking the form of a permutational chant in the German language, and is designed to evoke open-ended questions. Both the text sequence and the speech, integral to the project's sound, are entirely the result of my programming efforts.

For instance, the German phrase "was wer wie macht" can be translated to English as "what, who, how does." Similarly, this phrase also poses an open-ended question, probing various aspects of a situation or activity.

Example of textual data as the primary input for the processes of Sonification and data visualization.

Similarly, you will hear the German phrase "was wer wie sieht," which can be translated to English as "what, who, how looks." This phrase poses an open-ended question that can be used to inquire about the appearance or visual aspects of something or someone, as well as the process of looking or seeing.

Another example of textual data as the primary input for the processes of Sonification and data visualization.

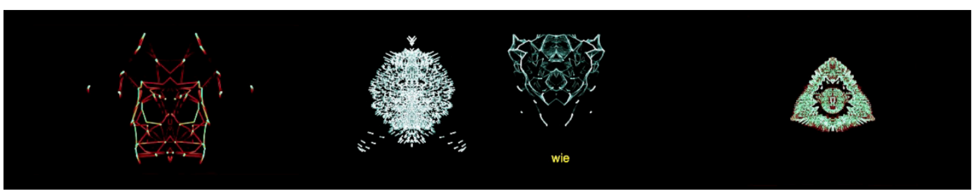
When I talk about open-ended questions, I refer to inquiries or themes within an artwork lacking a single, definitive answer. These questions stimulate subjective interpretation, critical thinking, and personal engagement, empowering viewers to derive their own meanings and emotions from the art. Open-ended questions in this project deliberately challenge preconceptions, introduce interactivity, and enhance the thought-provoking nature of an art experience.

4.3.8: Installation Overview: “This is aRt”

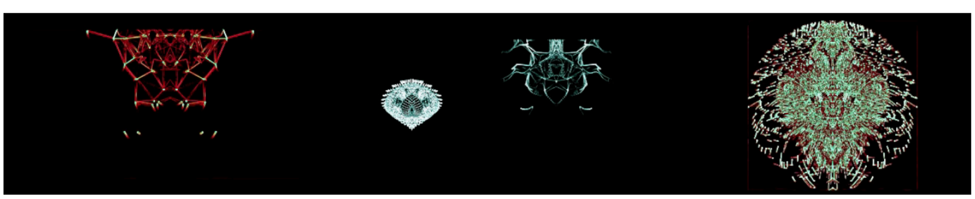
The entire installation has a duration of 4 minutes and 30 seconds and is a multimedia art experience consisting of media art and four accompanying posters.

4.3.8.1: Media Art: Large-scale Video

- The centrepiece of the installation is a large-scale video displayed on a wall screen measuring 7.3 meters by 1.4 meters in the Visualization Lab at the Digital Scholarship Centre, UofA. This impressive wall screen comprises 12 individual screens, delivering a total resolution of 12K.
- Dimensions: The large-scale video measures 11520 × 2160 and is divided into three sections; left, middle, and right.
- Content: The middle screen features three videos, including two showcasing results of data visualizations and one presenting generated text and speech. The left and right screens display distinct videos highlighting various data visualizations.



Left ***Middle*** ***Right***



Large Scale Video on Viz Lab Wall Screen

4.3.8.2: Data Viz Prints: Posters

Accompanying the video installation are four posters. These posters feature images showcasing diverse data visualizations created using the R programming language.[342] Additionally, the posters provide essential information about the project, its description, scientific background, and methodology.

4.3.8.3 Loudspeaker: Stereo Audio Channels

The musical component of the piece is arranged for stereo audio channels, enhancing the overall sensory experience. The Visualization Lab at the DSC is equipped with multiple ceiling speakers strategically positioned to immerse the audience in a captivating and dynamic auditory environment.

4.4: Conclusion and Future Implications:

Over the past twenty years, there has been a notable increase in the utilization of data sonification, where data is translated into auditory forms akin to visual representations, particularly within artistic circles and for the purpose of making scientific ideas more accessible. This phenomenon, extensively examined in academic literature spanning both scientific and humanistic disciplines, signifies a broader trend towards greater interaction and collaboration between the sciences and the arts. However, data sonification can also be interpreted as the latest progression in a historical dialogue concerning the relationship among nature, science, and human perception. This thesis aims to examine the appeal of data sonification, arguing that it engages public interest by offering aesthetic experiences and providing unique interpretations and insights into data through a variety of technological and musical approaches. Additionally, this study seeks to address concerns about the lack of aesthetic sophistication in sonification design by showcasing a collection of compositions that utilize sonification as a creative tool.

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[342] See step 4 in section “4.3.3: Creation model: Methodology”

Looking ahead, the integration of sonification techniques within the digital humanities field holds promising prospects. As technology continues to advance, there is potential for further refinement and innovation in the realm of data sonification, particularly in its application to interdisciplinary studies within the digital humanities. Future research could explore how sonification can enhance the understanding and interpretation of complex datasets in fields such as history, literature, and cultural studies. By incorporating sonification alongside traditional data visualization methods, digital humanities scholars can offer more nuanced and immersive experiences for both researchers and the public. Moreover, the collaboration between scholars, artists, and technologists in refining sonification methodologies could lead to the development of new tools and approaches for engaging with data in meaningful ways. By embracing sonification as a tool for interdisciplinary exploration, the digital humanities community can pave the way for novel insights and interpretations that bridge the gap between data-driven analysis and humanistic inquiry.

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