Human-Computer Interaction Series
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David Worrall

Sonification Design

From data to intelligible soundfields

The contemporary design practice known as *data sonification* allows us to experience information in data by listening. In doing so, we understand the source of the data in ways that support, and in some cases surpass, our ability to do so visually.

In order to assist us in negotiating our environments, our senses have evolved differently. Our hearing affords us unparalleled temporal and locational precision. Biological survival has determined that the ears lead the eyes. For all moving creatures, in situations where sight is obscured, spatial auditory clarity plays a vital survival role in determining both from where the predator is approaching or to where the prey has escaped. So, when designing methods that enable listeners to extract information from data, both with and without visual support, different approaches are necessary.

A scholarly yet approachable work by one of the recognized leaders in the field of auditory design, this book will

- Lead you through some salient historical examples of how non-speech sounds have been used to inform and control people since ancient times.
- Comprehensively summarize the contemporary practice of Data Sonification.
- Provide a detailed overview of what information is and how our auditory perceptions can be used to enhance our knowledge of the source of data.
- Show the importance of the dynamic relationships between hearing, cognitive load, comprehension, embodied knowledge and perceptual truth.
- Discuss the role of aesthetics in the dynamic interplay between listenability and clarity.
- Provide a mature software framework that supports the practice of data sonification design, together with a detailed discussion of some of the design principles used in various examples.

David Worrall is an internationally recognized composer, sound artist and interdisciplinary researcher in the field of auditory design. He is Professor of Audio Arts and Acoustics at Columbia College Chicago and the elected president of the International Community for Auditory Display (ICAD), the leading organization in the field since its inception over 25 years ago.

Code and audio examples for this book are available at https://github.com/david-worrall/sonipy/springer Information

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Human–Computer Interaction Series

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HCI is a multidisciplinary field and focuses on the human aspects in the development of computer technology. As technology becomes increasingly more pervasive the need to take a human-centred approach in the design and development of computer-based systems becomes ever more important.

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David Worrall

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From Data to Intelligible Soundfields

Springer

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For Bek
My Angkor, Wat

Preface and Acknowledgements

This book is about the contemporary design practice known as *data sonification,* which assists us to experience information by listening, much as we understand relationships between spatial features by viewing a graph of them. Data sonification begins with the observation that sounds can convey meanings in a multiplicity of circumstances: Exploring the structure of deep space, detecting a stock-market bubble, assisting injured patients to recover more quickly with less pain, monitoring the flow of traffic to help detect potential congestion, improving sporting performance, tracking storms, earthquakes and other changes in the environment … and the list could go on: hundreds of applications that rely on studies in acoustics and psychoacoustics, philosophy of perception, cognitive psychology, computer science, creative auditory design and music composition.

Data sonification grew out of an interest by composers in generating musical forms with the assistance of computers: *algorithmic compositions* based on both traditional musical languages, and the exploration of mathematical models of natural and abstract worlds. With ears searching for new means of expressing the contemporary world, they explored such fields as fractal geometry, neural networks, iterated function and reaction–diffusion systems, and flocking and herding. As computer processing speeds and storage capacity increased, and digital networks evolved, it became possible to use large datasets from real and real-time systems, not just abstract idealized models, and this led us into the currently emerging era of Big Data.

One of the motivations for this book was to understand some of the perceptual and conceptual correlates of intelligible data sonification so as to encapsulate the knowledge-bases that underpin them in software design. For example, the psychoacoustic, gestural and psycho-physiological substrates such as cognitive-load sensitivity and emotional valence, with low-level latent functions that can be compiled into higher level interactive modelling tools. Design is an inherently 'messy' and iterative activity that, while a process, may never be entirely procedural. So, the purpose here is not to trivialize the skills of an experienced designer, but to hierarchize the masking of many of the functional decisions made in designing, including such processes as equal-loudness contouring and modal convex pitch and time transforms. It is hoped that in doing so, novice designers might consider more adventurous possibilities and experienced designers will be enabled to implement complex procedures more flexibly: to test multiple different approaches to sonifying a dataset.

Part I: Theory

Chapter 1: The idea that sound can reliably convey information predates the modern era. The term data sonification has evolved along with its applications and usefulness in various disciplines. It can be broadly described as the creation and study of the aural representation of information, or the use of sound to convey non-linguistic information. As a field of contemporary enquiry and design practice, it is young, interdisciplinary and evolving; existing in parallel to the field of data visualization, which is concerned with the creation and study of the visual representation of information. Sonification and visualization techniques have many applications in 'humanizing' information, particularly when applied to large and complex sets of data. Drawing on ancient practices such as auditing, and the use of information messaging in music, this chapter provides an historical understanding of how sound and its representational deployment in communicating information has changed. In doing so, it aims to encourage critical awareness of some of the socio-cultural as well as technical assumptions often adopted in sonifying data, especially those that have been developed in the context of Western music of the past half-century or so. Whilst acknowledging the Eurocentricity of the enquiry, there is no suggestion that the ideas discussed do not have wider applicability.

Chapter 2: Encompassing ideas and techniques from music composition, perceptual psychology, computer science, acoustics, biology and philosophy, data sonification is a multi- even trans-disciplinary practice. This Chapter summarizes different ways sonification has been defined, the types and classifications of data that it attempts to represent with sound, and how these representations perform under the pressure of various real-world utilizations.

Chapter 3: One task of data sonification is to provide a means by which listeners can obtain new ideas about the nature of the source of derived data. In so doing they can increase their knowledge and comprehension of that source and thus improve the efficiency, accuracy and/or quality of their knowledge acquisition and any decision-making based on it. The purpose of this chapter is to develop an historical understanding of what information is as a concept, how information can be represented in various forms as something that can be communicated with non-verbal sonic structures between its source and its (human) receiver and thus retained as knowledge. Whilst a complete philosophical and psychological overview of these issues is outside the scope of the chapter, it is important, in the context of developing computational design strategies that enable such communication, to gain an understanding of some of the basic concepts involved. A quasi-historical epistemology of human perception and the types of information these epistemologies engender is followed by a discussion of the phenomenal nature of sounds and sonic structures their ability to convey information of various sorts.

Chapter 4: The previous chapter traced a path towards an understanding of the inadequacy of epistemological approaches to knowledge formation that do not account for the deeply embodied nature of perception, to succeed in solving any but highly constrained problems. The slower-than-expected rise in the effectiveness of artificial intelligence provided the impetus for a more critical examination of the ontological dimensions of perception and human knowledge, which necessitated the recognition of another form of truth which is not derived empirically but from meaningful action. This chapter enunciates this Pragmatist approach as it can be applied to sonification design: a generative activity in which bespoke design skills are supported by scientific research in biology, perception, cognitive science—in the field of conceptual metaphor theory in particular, and aesthetics. It proceeds to outline pertinent features of a broad design methodology based on the understandings developed that could yield to computational support.

Chapter 5: The need for better software tools for data sonification was highlighted in the 1997 *Sonification Report*, the first comprehensive status review of the field which included some general proposals for adapting sound synthesis software to the needs of sonification research. It outlined the reasons the demands on software by sonification research are greater than those afforded by music composition and sound synthesis software alone. As its *Sample Research Proposal* acknowledged, the development of a comprehensive *sonification shell* is not easy and the depth and breadth of knowledge, and skills required to effect such a project are easily underestimated. Although many of the tools developed to date have various degrees of flexibility and power for the integration of sound synthesis and data processing, a complete heterogeneous Data Sonification Design Framework (DSDF) for research and auditory display has not yet emerged. This chapter outlines the requirements for such a comprehensive framework, and proposes an integration of various existing independent components such as those for data acquisition, storage and analysis, together with a means to include new work on cognitive and perceptual mappings, and user interface and control, by encapsulating them, or control of them, as *Python libraries,* as well as a wrappers for new initiatives, which together, form the basis of *SoniPy*, a comprehensive toolkit for computational sonification designing.

Part II: Praxis

Chapter 6: Having established the design criteria for a comprehensive heterogeneous data sonification software framework in the previous chapter, this chapter introduces two pillars of such a framework, the *Python* and *Csound* programming languages, as integrated through a *Python–Csound* Application Programming Interface. The result is a mature, stable, flexible and comprehensive combination of tools suitable for real and non-realtime sonification, some of the features of which are illustrated in the examples of subsequent chapters.

Chapter 7: Despite intensive study, a comprehensive understanding of the structure of capital market trading data remains elusive. The one known application of audification to market price data reported in 1990 that it was difficult to interpret the results, probably because the market does not resonate according to acoustic laws. This chapter illustrates some techniques for transforming data so it *does* resonate; so audification may be used as a means of identifying autocorrelation in trading–and similar–datasets. Some experiments to test the veracity of this process are described in detail, along with the computer code used to produce them. Also reported are some experiments in which the data is sonified using a homomorphic modulation technique. The results obtained indicate that the technique may have a wider application to other similarly structured time-series datasets.

Chapter 8: The previous chapter explored the use of audification of a numerical series, each member representing the daily closing value of an entire stock market, to observe the cross-correlation (trending) within the market itself. This chapter employs parameter-mapping sonification to study the perceptual flow of all trades in individual stock groupings over a trading day by applying various filters and selection methodologies to a detailed 'tick' dataset. It outlines the use of a size/mass metaphorical model of market activity and the simultaneous use of two opposing conceptual paradigms without apparent conceptual contradiction or cognitive dissonance to demonstrate, given conducive conditions, the power of intention over perception and sensation, in auditory information seeking.

Chapter 9: The design of a real-time monitor for an organization's digital network can produce several significant design challenges, both from the technical and human operational perspectives. One challenge is how to capture network data with minimal impact on the network itself. Also, from an operational perspective, sounds need to perform *en suite* over long periods of time while producing only minimal listener fatigue. This chapter describes two related network data sonification projects which resulted in a set of audiovisual "concert" compositions (*Corpo Real*), an immersive installation, and a perceptual monitoring tool (*Netson*). This tool uses both sonification and visualization to present monitoring humans with features of data flow that allow them to experience selectable operational network characteristics. In doing so, it can be used to assist in the peripheral monitoring of a network for improved operational performance.

Code and audio examples for this book are available at https://github.com/david-worrall/springer/.

Acknowledgements

Gregory Kramer had a particular vision and commitment to establishing auditory display as a legitimate discipline. His organizing of the first conference in 1992, followed by the editing and publication of the extended proceedings, *Auditory*

display: Sonification, Audification, and Auditory Interfaces, produced a go-to reference for researchers in the field until the publication, in 2011, of *The Sonification Handbook*, with major contributions by many members of the community under the inciteful editorship of Thomas Hermann, Andy Hunt and John Neuhoff.

Over the past 10 years or so, various strands of the work in this book have appeared in papers for the International Conference for Auditory Display and I am grateful to many of the members of that diverse community for their annual collegiality, vigorous debate and general bonhomie. In 2009, my first attempt at a succinct overview of the field (Chap. 2) was published in *The Oxford Handbook of Computer Music and Digital Sound Culture*, edited by Roger Dean. Roger was brave enough, with Mitchell Whitelaw, to supervise my Ph.D. which eventually also formed the foundation for parts of Chaps. 3, 5, 7 and 8, for the latter of which, the Capital Markets Cooperative Research Centre in Sydney funded the experiments and provided the data. The securities trading data techniques discussed in Chap. 7 were first published in the Springer's 2010 *Lecture Notes in Computer Science* volume on *Auditory Display*. The research and development for the network sonifications reported in Chap. 9 was undertaken, in addition to other work with Norberto Degara, during 2013–16, whilst a Professorial Research Fellow, at Fraunhofer IIS, in Erlangen, Germany, at Frederik Nagel's International Audio Laboratories, under the leadership of the Institute Director, Albert Heuberger.

I am often struck by how even a small sense of the influences on a writer can provide meaningful insights into their work. In that spirit, I mention some. However, lest it resulted in too autobiographical an appearance, I omit details of years of music-making and restless inquisitiveness in the arts of mathematics and animal anatomy. I spent the mid-1980s as a member of the Composition Department in the Faculty of Music, and in the Computer Science Department at The University Melbourne, followed by 15 years of research and teaching at the School of Music and the Australian Centre for the Arts and Technology (ACAT) at the Australian National University in Canberra, and, more recently, in the Audio Arts and Acoustic Department at Columbia College Chicago. In order not to draw the wrath of any individual inadvertently missed from what would be a long list, most of the names accompany mine on conference papers, in journal articles and concert programs, so I defer to another time to name them all individually. I have been fortunate to work with a few people who have dedicated their talents to working behind the scenes in technical and assistive capacities, and without whom everything would have ground to a halt: Les Craythorn in Melbourne, Niven Stines and Julie Fraser in Canberra, and David Knuth and Maria Ratulowska in Chicago.

This work is grounded in an intellectual and artistic experimental tradition, from which I have been blessed with more than my fair share of excellent mentors. Out of respect for those traditions and in honor of them, I also invoke the spirits of those who have passed, thus: Richard Meale (and through him), Winifred Burston, Ferruccio Busoni, Frans Liszt, Carl Maria von Weber, Carl Philipp Emmanuel Bach and his father Johan Sebastian, John Bull, Carlos Gesualdo … That thread has been crisscrossed in my own life by various others, including Tristram Cary, Iannis Xenakis, Olivier Messiaen and Jean-Claude Risset. Richard was a mentor, friend

and as fierce critic as he was an experimentalist: in music, chess and cooking. Although we fought bitterly as he was overcome by the affliction of postmodernism in his latter years, he wrote some of the best music of his generation. He is deeply missed.

Thanks go to the editorial staff at Springer for their encouragement and long-suffering: tolerance way beyond reasonable expectations. I was not to know, at the time of discussing publishing with them in 2015, that this book would be written in ten residences on three continents. That it has appeared at all is a minor miracle, performed by my beautiful, gracious, strong and unbelievably perceptive wife, Rebekah, who, with Isaac and Catheryn have been my constant companions and family support throughout. As we have lived out our semi-nomadic existence, their day-long 'visits' to the local library, wherever we were, so "Dad could work on *the book*" has not been easy for them, and we're looking forward to a summer of bikes and music-making.

Oak Park, Illinois David Worrall
March 2019

> I like to listen. I have learned a great deal from listening carefully. Most people never listen.
> (Ernest Hemmingway, my Oak Park neighbor before I moved in.)

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Theory

Chapter 1
Data Sonification: A Prehistory

Yasyāmataṁ tasya mataṁ; mataṁ yasya na veda saḥ
["One who (thinks he) knows not, knows; one who (thinks he) knows, knows not." (Muktananda 1972)].

Abstract The idea that sound can reliably convey information predates the modern era. The term *data sonification* has evolved along with its applications and usefulness in various disciplines. It can be broadly described as the creation and study of the aural representation of information, or the use of sound to convey non-linguistic information. As a field of contemporary enquiry and design practice, it is young, interdisciplinary and evolving; existing in parallel to the field of data visualization, which is concerned with the creation and study of the visual representation of information. Sonification and visualization techniques have many applications in "humanizing" information, particularly when applied to large and complex sets of data. Drawing on ancient practices such as auditing, and the use of information messaging in music, this chapter provides an historical understanding of how sound and its representational deployment in communicating information has changed. In doing so, it aims to encourage critical awareness of some of the socio-cultural as well as technical assumptions often adopted in sonifying data, especially those that have been developed in the context of Western music of the last half-century or so. Whilst acknowledging the Eurocentricity of the enquiry, there is no suggestion that the ideas discussed do not have wider applicability.

1.1 An Ancient and Modern Practice

We are at a time in the evolution of humans and their tools when the power of digital information processing and algorithmic decision-making is demonstrating an ability to radically change our lives: From genetic finger-printing, gene-splicing and pharmacology, to driverless vehicles, patterns in our consumption and how we amuse ourselves. Even now, so early in this new Dataist era, organizations with networked computational intelligence, already have access to more data about

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ourselves than we ourselves have access to, and are beginning to demonstrate a power to make better decisions for us than we make for ourselves. What, then, one might reasonably ask, is the use of exploring such ancient, intensely human-centered approaches to information-gathering and decision-making as listening? How old-fashioned; how quaint! This is an increasingly pertinent question and has been latently fundamental to why this book was written. The answers are not necessarily obvious as they lie at the heart of the difference between a conception of life merely in terms of information flow and data storage as might be imagined by the cognitivists (Worrall 2010), and one in which mind, body and (now technologically enhanced) consciousness play a fundamental role in active perception, knowledge acquisition, meaning-creation and decision-making.

In a contemporary media-saturated environment, sound plays a wider variety of different social and communicative roles today than it ever did in the past. Although computer-generated data sonification is a relatively recent formalized practice,[1] cultural antecedents can be identified in all periods of history. This chapter provides a focused description of how the deployment of sound and sonic structures to communicate information has changed over time. It the spirit of the adage “know from whence you came”, doing so will assist us to critically examine some of the socio-cultural assumptions we have adopted in our own age.[2]

In the process of uncovering the accuracy or truth[3] of our assumptions about perception, it is not uncommon for commentators to be seduced into a type of sense war, in which hearing and listening are pitted against vision and seeing. Such casting can take many forms. What is to be gained by Marshal McLuhan’s myopia, for example?

> The ear is hypersensitive. The eye is cool and detached. The ear turns man over to universal panic while the eye, extended by literacy and mechanical time, leaves some gaps and some islands free from the unremitting acoustic pressure and reverberation (McLuhan 1968, 168).

Thankfully, the discussion has moved on, at least in some circles.[4] Each have their place and so to be encumbered with such a burden is not useful, particularly when a culturally-driven focus on one sense assumes a decline of another. While this book

[1]The first international conference was held in 1992 (Kramer 1994a).

[2]As Jonathan Sterne indicates, while there is a vast array of literature on the history and philosophy of sound, it is without some kind of overarching, shared sensibility about what constitutes the history of sound, sound culture, or sound studies (Sterne 2003). It is not the purpose of this chapter to remedy that!

[3]Truth, as in the Heideggerian meaning of the term *alétheia*: a non-propositional unconcealment. This concept of ‘truth’ takes on the dynamic structure of uncovering that is disclosive rather than propositional or judgmental.

[4]A comprehensive survey of increasingly nuanced arguments is outside the confines of this work. In its notes and bibliography, *The Audible Past* Stern (2003) lists a significant amount of literature in English on the topic since the Enlightenment. Over a longer historical timeframe, Veit Erlmann’s, *Reason and Resonance* traces historical changes in the understanding of the relationship between developing conceptions of sound and hearing physiology (2010).

is about the transmission of intelligibility through sonic structures, it does not contend that sound should replace vision in enquiry, any more than the assertion that music expression is best when unencumbered by the "strictures" of musical notation. This is not to deny that there are sensory differences; they all assist us differently, else it is unlikely evolution would have sustained their individual continuance. In fact, it can be instructive to identify them. For example, it is hearing, not vision, that affords omnidirectional coherent perceptual experiences. For all moving creatures, including our ancestors, both ancient and modern, in situations where sight is obscured, spatial auditory clarity plays a vital survival role in determining both from where the predator is approaching or to where the prey has escaped. On the other hand, we can suppose that, to a creature sleeping in a cave, being alerted early by the amplifying echoic resonance of the space that something of a certain mass was entering, was more important than details of its exact position. These evolutionary adaptations are sometimes very deep in our biology, such as the presence of defensive startle reflexes which are very resistant to habituation, and the fascinating orienting reflex (eliciting a "what is it?" reaction) (DeGangi 2017, 309–60; Sokolov et al. 2002) which have cultural resonances such as, for example, when the biological preferencing of the ears to lead the eyes[5] forms the basis of as a scene transition technique to enhance narrative continuity in film.

While sensory differences do exist, it is instructive to consider that the domination of one sense over another—especially when considering hearing and vision—is not a biological phenomenon, but a cultural one. As will be seen in the upcoming discussion of the role of sound in the Church's dominion over Europe, when the control of the whole community was through the sense of hearing, such control was more easily broken away from by individual 'voices' using another sense (vision) and, supported by development in visual technologies, which in-turn, through notation, supported the development of individual musical voices that were able to create complex sonic 'inputs' to the resonant cathedrals while maintaining 'signal' coherence which supported understanding.

1.2 Ancient Egyptian Use of Sound to Convey Information

There are many reasons why, in certain circumstances, sound might be the preferred representation and communication medium for information, including the known superiority of the hearing sense to discriminate particular kinds of structures. For example, it is easy for most of us to personally verify that a purely visual side-by-side comparison of two sets of written records requires high levels of concentration and that doing so is very prone to error, especially over extended periods of time. One the other hand, listening to vocalizations of such

[5]Resulting, presumably, from the superiority of the omni-directionality of hearing in visually-obscured environments.

representations is much easier. The presence of such auditing[6] can be inferred from records of Mesopotamian civilizations going as far back as 3500 BCE. To ensure that the Pharaoh was not being cheated, auditors compared the "soundness" of meticulous independently-scribed accounts of commodities such as grains moving in and out, or remaining, in warehouses (Boyd 1905). When granary masters, otherwise strictly isolated from each other, assembled before the Pharaoh and alternated in their intoning of such records, differences in their accounting records could be easily identified aurally. A faster and more secure method that eliminates any "copy-cat" syndrome in such alternation, is to have the scribes read the records simultaneously—a type of modulation differencing technique. Although we have no hard evidence that these techniques were practiced, such a suggestion does not seem unreasonable, and would represent possibly the earliest form of data sonification.

1.3 The Ancient Greek Understanding of Music

While sound has also played an important role in both theoretical and empirical inquiry for millennia, the ancient Greeks wrote extensively on the subject, notably in reference to music, the most complex and abstractly considered form of non-linguistic aural communication made by humans. It can be divided into three modes of enquiry that are of direct concern to sonification: numerical rationality, empirical experience and expressive power.

1.3.1 Numerical Rationality

At least as far back as Pythagoras (born ~ 569 BCE), arithmetic was considered to be number in itself, geometry to be number in space, and harmony to be number in time. The concept of The Harmony of the Spheres, in which the Sun, Moon and planets emit their own unique "sounds" based on their orbital revolution,[7] played a unifying role in the development of the arts and sciences, and incorporated the metaphysical principle that mathematical relationships express qualities or "tones"

[6] Literally, *the hearing of accounts* from the Latin *auditus.*

[7] Known generally as the "music of the spheres". As Gaius Plinius Secundus observed, "… occasionally Pythagoras draws on the theory of music, and designates the distance between the Earth and the Moon as a whole tone, that between the Moon and Mercury as a semitone, …" the seven tones thus producing the so-called diapason, i.e. a universal harmony (Pliny [77AD] 1938). Ptolemy and Plato also wrote about this practice.

of energy ratios. Pythagoras' approach to music was as a numerically rational analysis of the way string lengths and sounds relate to each other physically, that is *acoustically*, and importantly, he classified the sensation of harmoniousness according to these ratios.

The application of number relations (i.e. ratios) and sound have been integral to the conceptualization and realization of Western music over all periods in radically different ways: From the development of richly fecund investigations in tuning and temperament to multiple voice polyphony and highly chromatic polytonalities; from serialized additive rhythms under group theory transformations to stochastic mappings controlled by Poisson's distribution.

1.3.2 Empirical Experience

Aristoxenus of Tarentum (c. 375–335 BCE) was a pupil of Aristotle. With the exception of his treatise on harmony, (Macran 1902) most of his writings have been lost. In contrast to Pythagoras, Aristoxenus' approach was more concerned with the structure of the listening *experience*, which he explained in terms of the various modes.[8] A pupil of his musician father and the later Pythagoreans who were keen on distilling their inherited scientific knowledge from its more mystical entrapments, Aristoxenus' own writings on music are somewhat empirical, perhaps influenced by Aristotle, with whom he also studied. He maintained, in contradistinction to the Pythagoreans, that the notes of the scale could be tuned by the ear rather than ratio measurement, and formulated a theory that the soul is related to the body as harmony to the parts of a musical instrument.[9] Here, for example, is his description of vocal pitch inflection such as glissandi:

> The continuous voice does not become stationary at the "boundaries" or at any definite place, and so the extremities of its progress are not apparent, but the fact that there are differences of pitch is apparent…; for in these cases we cannot tell at what pitch the voice begins, nor at what pitch it leaves off, but the fact that it becomes low from high and high from low is apparent to the ear. In its progress by intervals the opposite is the case. For here, when the pitch shifts, the voice, by change of position, stations itself on one pitch, then on another, and, as it frequently repeats this alternating process, it appears to the senses to become stationary, as happens in singing when we produce a variation of the mode by changing the pitch of the voice. And so, since it moves by intervals, the points at which it begins and where it leaves off are obviously apparent in the boundaries of the notes, but the intermediate points escape notice… (Vitruvius 1914: Chap. 4).

[8]Xenakis (1971, 183–189) has a more detailed explanation of Aristoxenus' modal thinking.

[9]The following quote from Vitruvius '*De architectura*' (Book V Chap. 4) contains a paraphrase of a extant fragment of a treatise on meter in writings on music that is attributable to Aristoxenus.

1.3.3 Expressive Power

Aristotle (384–322 BCE) was interested in the ability of sound (music and poetry), to *express* states of mind and evoke these states in the soul (mind) of the listener:

> …for when we hear [music] our very soul is altered; and he who is affected either with joy or grief by the imitation of any objects, is in very nearly the same situation as if he was affected by the objects themselves; … now it happens in the other senses there is no imitation of manners; … for these are merely representations of things, and the perceptions which they excite are in a manner common to all. Besides, statues and paintings are not properly imitations of manners, but rather signs and marks which show the body is affected by some passion… But in poetry and music there are imitations of manners; … those who hear them are differently affected, and are not in the same disposition of mind when one is performed as when another is; the one, for instance, occasions grief and contracts the soul, … others soften the mind, and as it were dissolve the heart: others fix it in a firm and settled state, … fills the soul with enthusiasm… The same holds true with respect to rhythm; some fix the disposition, others occasion a change in it; some act more violently, others more liberally (Aristotle 2018, Politics, VIII:V).

1.4 The Ear as the Central Organ of the Church

In pre-medieval Europe, the Roman Catholic Church eventually filled the political and spiritual vacuum caused by the collapse of the Roman Empire around 500 CE and went to extraordinary lengths to establish supreme papal power, resulting in the construction of massive reverberant cathedrals, which replaced the echoic caves of the past to become temples in which the resonant voice of an omnipresent God, through the Pope, and his priests and their choirs, was delivered to a largely passive, observing audience; silenced by the unintelligible Latin and the presence of the holy sacrament, for the safety of their immortal souls. Even though this church almost universally forbade the use of all instruments of "profane" music in worship, sometime during the tenth century large *Blockwerk* organs began to be permanently installed in churches and cathedrals.[10] By producing the lowest-pitched and most powerful musical sounds of the period, these organs resonated the buildings in which they were installed, and impressed on congregations a power found only in the church. In addition, these modern caves were engineered to produce an awe-inspiring, comforting, inclusive "community" feeling through spatial aural reverberant incoherence, and by which potentially questioning or dissenting individuals were subsumed into the anonymity of the Mass.[11]

When Johannes Gutenberg (1398–1468) invented his mechanical movable-type printing press in 1440, only six to seven percent of European adults were literate

[10]This somewhat convenient simplification of the role of music and musical instruments in the Middle Ages is more evenly discussed in Grout (1960).

[11]The pun is intended.

(Schlossberg 2011) and eighty percent of English adults couldn't even spell their names.[12] Thus, the closely connected (visual) activities of writing and reading were engaged in only by the educated, ruling classes while the overwhelmingly illiterate common people's only connection to writing was when it was read aloud to them. While they maintained their profane cultures by telling each other stories from within their rich oral/aural traditions, played musical instruments and danced, their only access to the word of God was through lectionary periscopes.[13] Gutenberg's invention flooded Europe with printed material. It made the Bible more available and encouraged an increase in literacy rates which eventually resulted in dissent from the Roman church's authority in the form of the sixteenth century's Protestant Reformation. The spread of literacy was accelerated by the emphasis on education in increasingly urbanizing societies; making way, in the seventeenth century, for an intellectual rebirth in the Europe in the form of the Renaissance which eventually lead, over an extended eighteenth century, to the Age of Enlightenment in which reason was advocated as a means of establishing an authoritative system of government, religion, ethics and aesthetics. This supported an intellectual and scientific impetus to obtain objective truths about the whole of reality, the spread of learning to the masses, and laid the material basis for modern knowledge-based economies.

Breaking the mental clutches that the church imposed by leveraging illiteracy and the use of sound to surround and sublimate independent voices, required men of vision, using empirical techniques, to "look" past the religious dogma of the church for objective theories of the natural world "out there". It also required the invention of observational instruments and techniques "favorable to the progress of the arts and sciences" (Wilson 1957, 227). For example, Galileo Galilei (1564–1642) built his own telescope in 1609, a year after it was patented in the Netherlands (Loker 2008, 15). Another such invention was the (re)discovery of the laws of linear perspective by the Filippo Brunelleschi of Florence (1387–1446) which enabled the depiction of visual depth on a planar surface. Lacking a theory of mathematical perspective, artists of the Middle Ages were more concerned with the static depiction of all-encompassing religious or spiritual metaphors rather than depicting the real, physical world, oriented towards an individual viewer. In addition to promoting and acknowledging the viewer, perspective provided a powerful technique to visually depict mechanical devices for the first time in a realistic manner, and assisted in the invention and dissemination of cosmographic scientific instruments for astronomy, surveying, navigation, map-making and time-telling.

In parallel to these advances in visual representation, the angelic voice-only sacred monophonic plainchants of the church were challenged by, and eventually subsumed into, the polyphonic complexities of the compositions of increasingly-individually-recognized composers who, in composing order on the

[12]This figure was calculated by combining literacy rates derived from Roser and Ortiz-Ospina (2018) and population demographics estimated by Urlanis (1941).

[13]Literally "cuttings" (from the Bible), from the Greek *perikopē* meaning a "section" or "cutting".

cathedral-induced echoic aural incoherence of multiple overlapping lines of the chants, explored, notated and extemporized new musical structures. These structures were not arbitrarily abstract however, but developed from careful attention to both the sounds and accents of the words being sung as well as the meanings in their texts.[14]

1.5 Music as Language and Rhetoric

The belief, that since music is a language and can be consciously treated as such, is not confined to post-medieval Europe. Many cultures have developed melodic and rhythmic modes and dance gestures through which associated concrete meanings and/or affective states are communicated to understanding audiences. For example, the ragas, talas and mudras (hand/finger gestures) of classical India are used to clearly communicate specific ideas, events, actions, or creatures. The ancient Greeks invented a whole system of how different musical elements affect the soul in different ways. The Renaissance of their ideals in Europe included the application of rhetorical devices, not only in speech, but in music and dance. A system of rhetorical devices, i.e. a representational vocabulary for making communication explicable and persuasive, was considered essential for organizing the syntax of (initially voice-only) compositions and, by addressing an audience's logical and emotional dimensions simultaneously, making the music semantically effective and able to communicate successfully. By the middle of the sixteenth century, such rhetorical devices had developed into often extravagant musical word paintings or *madrigalisms* as they were known.[15] Nevertheless, the study and use of rhetoric to make musical discourse more concretely meaningful continued through the seventeenth and well into the eighteenth century. Haydn, often described by his contemporaries as "a clever orator" and "the Shakespeare of music," is probably the last major European composer whose music was regularly discussed by his contemporaries in terms derived from the classical tradition of rhetoric (Beghin and Goldberg 2007; Saint-Dizier 2014). The artistry of his musical rhetoric is amply displayed in his oratorio, *The Creation* (Zbikowski 2019).

The purpose of this discussion is not to suggest that linguistic utterances are music, or vice versa. However while music and linguistic speech have different

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[14]The isorhythmic motets of Guillaume de Machaut and John Dunstable, for example, in which each voice in a canon is in a different rhythm.

[15]Of special interest, is the extravagantly manneristic and harmonically experimental music of Carlo Gesualdo (1566–1613) which was also encouraged by the visionary experimental composer and music theorist Nicola Vicentino (1511–1575/6). For a fuller discussion, see Brown (1976). Also of interest is the composition of Eye Music, in which the use of black and white musical notations was used to suggest darkness and light; sadness and joy (Einstein 1949). See Sect. 1.7.

cultural functions, rhyme and rhythmic speech have also been important in musical devices in many cultures and the two forms of expression are often blended. The adulatory praise poems of Africa in which professional bards, who may be both praise singers to a chief and court historians of their tribe, chant a series of epithets in an attempt to capture the essence of an object, event or person (Weinberg 1978). In the tradition Chinese form *shuochang*, performances commonly intermix speaking and singing, accompanied by percussion and sometimes plucked or bowed string instruments. Such praise songs and "story-singing" are the precursors of Rap[16] music, a contemporary form of vocal delivery that incorporates rhyme, rhythmic speech, and street vernacular; performed or chanted over a backbeat, musical accompaniment or *a cappella*.[17] Stylistically, Rap occupies a gray area between speech, prose, poetry, and singing (Edwards 2009).

1.6 The Rise of Abstract Instrumental Music

During the European Middle Ages, secular public musical activity consisted of heroic and lyrical minstrel songs and instrumental music to accompany dancing. During the Renaissance, regal courts became significant centers of economic and cultural activity outside of the Catholic Church, which lead to its eventual failure to suppress most forms of instrumental music as undesirably profane. So it was, that the Baroque style, particularly in music, painting and architecture, was encouraged by the post-Reformation Church as a means to stimulate religious fervor.

As monarchs and their courtiers required intellectual stimulation and entertainment, the composers serving in the courts became more experimental. Using a greater variety of musical instruments, and innovative harmony, they increasingly considered musical forms as modes of personal expression. The codification of staff notation, supported by a burgeoning print industry, encouraged the extended development and dissemination of more abstract musical structures: The simile-like representations of word-painting and other rhetorical devices gave sway to these more conceptually metaphoric and self-referential (symbolic) motifs, which became built into the very fabric of Western musical language.[18]

While initially following in the spirit of courtly dances, the decline on the reliance of textual subjects in favor of formal reflexivity also became a means of embodying aesthetic affects (Erlmann 2010, 94). As a consequence, there arose a

[16]The word has been in British English since the sixteenth-century, meaning "to lightly strike" and is now used to describe quick speech or repartee (ACOD 1992). Since the late 20th century the term *shuochang* is used in China to refer to rap music (Wikipedia 2019).

[17]Literally "in the manner of the chapel" that is without instruments, thus emphasizing the point made in Sect. 1.4 concerning the Church's banning of musical instruments in worship.

[18]Some such motifs have become well known. Two such are J.S. Bach's "B-A-C-B^{b}" (The note B^{b} is represented by the letter 'H' in German), and Beethoven's "Fate" motif from the opening of his *Fifth Symphony*.

belief that music was not a language in the sense that it no longer had properties of defining and referring to specific meanings about which interpretations and responses could be made.[19] The need for some understanding of what we might call the semiological codes of music was apparent however, for without them it would have been difficult to claim for music to be more than just beautiful arrangements rather than important expressions of human experience and expression in the humanist tradition. In discussing musical language, Durant (1984, 10) says:

> On the one hand, there is 'language' as an assumed range of properties and associated effects, determined … by psychological or acoustical resources. These supply continuity for the 'language' and an overall framework for activity. Music made outside the framework is simply part of another 'language'. What would be most interesting about this 'language' would be the precise nature of the acoustic and psychological resources, even if these—failing some way of determining correspondences between forms and effects—will not explain very much about actual, particular pieces of music. In the other emphasis, there is language as a set of properties and associated effects (still conditioned by psychological and acoustic resources), whose most significant features are those of social, regional and historical variation around those resources.

And later (op.cit.: 13–14), recalling Claude Debussy's "Works of art make rules but rules do not make works of art" (Paynter 1992, 590), Durant observes:

> …In this latter emphasis, musical works do not simply exist within, or use, the musical 'language': they make and remake it, in particular realizations and directions of potential.

Following the rise of public concerts and music to be listened to for its own sake, the status of instrumental music grew in the eighteenth century, along with the Cartesian idea that abstract reflexive forms were the pre-eminent *raison d'être* of musical expression, so that "critics increasingly came to think of music as having emancipated itself from mimetic representation" (Erlmann op.cit.:189).

1.7 "Organizing the Delirium"

During the nineteenth and early twentieth century, there was also a shift by composers from musically representing various gestural and aesthetic affects (as portrayed in the different formal dance forms, for example) to the representation of individuals' changing emotional states. The principal structural means of organizing compositions was functional tonal harmony, which relies on a set of codes or functions to create expectations in the listener of, given what has just occurred, what might occur next. The German Romantic interest in the personal expression of intense emotional states led composers to search for new expressive means such as

[19]The evolution of the late Middle English term *motive* from the Old French *motif* (adjective used as a noun) has its origin in the Latin *motivus*, from *movere* 'to move' (ACOD 1992).

rapidly shifting modulations and eventually the abandonment of functional harmony as means of organizing both moment-to-moment flow within a work as well as the form of the entire composition—and eventually of tonality itself.[20]

In addition to its social and cultural imperatives, there is a distinct trend for Western experimental composers to conceive of their music as complex-patterned time-ordered series of acoustic events that vary in pitch, loudness and timbre; that are absorbed and elicit emotions when listened to. This paradigm is embedded in scored compositions that are abstractly composed and transmitted to listeners by expert musicians by a variety of means, including concerts, recordings, broadcasts, and internet streaming. Following the examples of the Second Viennese School in the first part of the twentieth century,[21] many composers used serial procedures based on permutation group orderings of the chromatic pitch gamut.[22] This led to a short but intense period when each of the (now "parameterized") dimensions of a composition (pitch, duration, dynamics and timbre) were all serially organized. The idea of music as a variable-parameterized space has been adopted by sonifiers engaged in parameter-mapping sonification, will be discussed below, and the attempt to use logical operations on parameterized datasets to make them perceptually coherent is discussed in detail in Chap. 3.

The composer/architect Iannis Xenakis, whose oblique contribution to sonification is discussed later, is a major and distinct European voice of musical composition of the second half of the twentieth century. He was clear that the serialists had made an important contribution to the search for new methods of organizing music by introducing abstraction (Xenakis [1971] 1991, 193). However, he did not agree with their declared necessity for using just serial techniques to organize musical material, and was critical of linearity of serial thinking: the way pitch dominated musical structuring, even when its influence on the sound was only secondary; that under serialism as they defined it, duration was, in general, even less structurally organized than in traditional forms, and that the resulting disjunct linear polyphony destroys itself by its very complexity.

John Cage often produced scores somewhat automatically by making marks on a page using the *I Ching*, or spatially related mappings such as those in a star map for *Atlas Eclipticalis* (1961), or the imperfections in the paper itself in *Music for Piano* (1952–62). In these works, the (often graphic) scores function as non-specific stimuli to performers rather than as a set of precise codes or instructions made by

[20]The connection between Freud and Schoenberg and their attempts to "organize the delirium" (as composer Pierre Boulez was known to have described it) relies on an affinity between Freud's structural model of the mind and Schoenberg's method, whose rules are based in the principles of symbolic logic, even if applied unconsciously. See Carpenter (2018).

[21]Principally Arnold Schoenberg, Anton Webern and Alban Berg.

[22]There are far too many composers to mention in this context as the techniques were employed and taught by numerous composers across the Western world. Two publications were influential: *Die Reihe* (Eimert and Stockhausen [1957] 1968, 1968) in English and German, and *Serial Composition and Atonality* (Perle 1962).

the composer to performers. As such, the relationship between the score and the sonic results are seldom perceivable by the listener, nor were they meant to be (Cage and Knowles 1969). This type of representational mapping has its historical precedents in Eye Music (Einstein 1949, 3:1971) and while, considered broadly, it is a type of sonification, it is outside the gamut of the current work.

1.8 From Program Music to Programmed Music

Not all composers were caught up in the psychological angst of the German romantics and expressionists, or the following existential modernist's position that ordinary musical listening was archaic and needed to be replaced with "structural listening" (Eisler and Adorno [1947] 1994, 20). So, the need to concretely "ground" musical expression in the earthly domain persisted in compositional references to the real, often rustic, world. In fact, compositions depicting nature in one way or another were so common that the term *Pastoral* is used as a description of a type of composition, and there are a number of recognized national Pastoralist schools.

While most critics and aestheticians of the time wrote disparagingly about the depictions of birdcalls and battles, which they regarded as a debasement of the art, such things were popular with the public, as were—and are—nature "atmospheres." Well known examples include Antonio Vivaldi's *Four Seasons* (1725), the second movement of Ludwig van Beethoven *Piano Sonata*, Op.28 (1801), Felix Mendelssohn-Bartholdy's overture *Fingal's Cave* (1833), Frederic Chopin's *Raindrop Prelude* (1838), and Nikolai Rimsky-Korsakov's *The Flight of the Bumblebee* (1900). But even after Arnold Schoenberg had composed *Erwartung* (1909) and *Five Orchestral Pieces* (1909), Ottorino Respighi composed *Pines of Rome* (1917), Ralph Vaughan Williams, *A Pastoral Symphony* (1922), Arnold Bax, *November Woods* (1917) and Charles Ives *Three Places in New England* (1912–16). A compilation list would include many of the best know works in the Western canon.

Although less common, the literal transcription of real-world sounds into music has been even more challenging to the abstract expressionists than Pastoral music. The cuckoo calls in Beethoven's Sixth Symphony (1808) and Olivier Messiaen's *Catalogue d'oiseaux* (1958) [Catalog of Birds] and his use of a wind machine in *Des canyons aux étoiles* (1974) [From the Canyons to the Stars] are obvious examples but the trend extended throughout the twentieth century with the inclusion of non-traditional sounds such as the fire siren in Edgard Varese's *Ameriques* (1921), the futurist's noise art[23] and then, especially following the invention of the tape recorder in the 1940s, by *musique concrète*—the term itself being coined by Pierre Schaeffer[24] to contrast the music he was making at *Radiodiffusion Française* in Paris with the "pure" (i.e. abstract) music of the period, especially that being

[23]As described in the 1913 manifesto *The Art of Noises* (Russolo 1916).

[24]Schaeffer's work is discussed in more detail in Chaps. 3 and 4.

produced by the German expressionist composers including those at the WDR in Cologne.[25] Schaeffer and others established the GRMC[26] in Paris in 1951 which attracted many notable composers of the period. He went on to establish the GRM,[27] one of several theoretical and experimental groups unified by the study of audiovisual communication and mass media.

1.9 Algorithmic Composition and Data Sonification

Xenakis's focus on using mathematics in composition included the application of group theory, game theory, symbolic logic and stochastics to musical composition (Xenakis [1971] 1991) was seminal in establishing a compositional "style" known as algorithmic composition which sowed the seed for the idea of representing abstract data relations in sound for investigative purposes.[28] Xenakis was a participant at GRM but, following Schaeffer's refusal in 1963 to use mathematics and the computer in the studio there,[29] established EMAMu, later CEMAMu,[30] specifically in order to undertake research into the application of mathematical ideas to music composition.

The other notable early algorithmic music research of the period was by Lejaren Hiller and Leonard Isaacson at the University of Illinois at Urbana-Champaign. They used the university's ILLIAC I computer to develop a "rules-based" system to create *cantus firmi*, four-voice harmonies, various rhythmic and dynamic schemes,

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[25]Studio für elektronische Musik des Westdeutschen Rundfunk (Studio for Electronic Music of the West German Radio). Following a brief period in Schaeffer's studio in 1952, Karlheinz Stockhausen joined Gottfried Michal Koenig and Herbert Eimert at the WDR. While the early electronic music he produced there employed purely electronically produced sounds (e.g. *Studie I* and *Studie II*), Stockhausen soon felt the need to work with a continuum between electronic and human vocal sounds (e.g. *Gesang der Jünglinge* in 1956) and by extension, the inclusion of materials other than sounds produced purely by electronic means (Stockhausen 1964). Electronic music from the Cologne studio thereby moved closer conceptually to the musique concrète from Paris.

[26]Groupe de Recherches de Musique Concrète, Club d 'Essai de la Radiodiffusion-Télévision Française at RTF.

[27]Groupe de Recherches Musicales.

[28]This musical style in also known as or generative- or procedural- or automated-composition. One assumes that today such compositions are composed, and perhaps realized, with the aid of computers, but this is not necessarily the case. Many of the calculations for Iannis Xenakis early works, such as *Metastaseis* (1953–54) and *Pithoprakta* (1955–56), were made using a hand-held calculator (personal communication). Using dice to randomly generate music from pre-composed options (Musikalisches Würfelspiel) was quite popular throughout Western Europe in the 18th century. (Wikipedia: Musikalisches Würfelspiel). Code can be written post mortem, however: Witness that for Wolfgang Mozart's German dances (Saunter 2018).

[29]Xenakis met Schaeffer in 1954 and composed five major pieces of *musique concrète* during the period (Gibson and Solomos 2013).

[30]Centre d'Etudes de Mathématique et Automatique Musicales (Center for Mathematical and Automatic Musical Studies).

and Markovian stochastic grammars which they realized in the *Illiac Suite* for string quartet in 1957.

Such computational proceduralism developed rapidly during the second half of the twentieth century in league with the development of cybernetics and cognitive science. The technical feasibility of being able to accurately repeat the synthesis of sounds by digital means enabled the birth of computer music, which was also heavily influenced by the "acoustic event" paradigm that became embedded in many of the compositional software tools used to create it. These tools have been widely adopted by researchers who use them in an attempt to obtain a better understanding or appreciation of relations in datasets of various sizes, dimensions and complexities—what is now called scientific sonification.

It is useful to distinguish data sonifications made for the purposes of facilitating the communication or interpretation of relational information in data, and data-driven music composition, ambient soundscapes and the like—the primary purpose of which is personal expression and other broader cultural considerations, whatever they may be. While scientific or pragmatic data sonifications and music compositions share a common reliance on the need to render structures and relations into sound, their purpose is often different, and so too the rationale for the evaluation of the sonic results. The current use of the term *sonification* to include such cultural concerns is somewhat unfortunate because it blurs purposeful distinctions. A desire to maintain these distinctions is not to suggest that there are not commonalities—the two activities can provide insights that are mutually beneficial. However, because the purposes of the activities are different, so too will be their epistemological imperatives and consequences, such as, for example, in the representational methodologies employed, in tool design, in user-interface and usability requirements and evaluation—all matters dealt with in subsequent chapters.

1.10 Purposeful Listening: Music and Sonification

There is no one-way, or reason, to listen to music. Even different musics have different contexts and thus require different ways of listening that may involve whole complexes of social dimensions that are simply not relevant to the perceptualization of data relations for pragmatic purposes. Furthermore, although music may be composed of syntactic structures, there is no universal musical requirement that these structures be made explicit, even aurally coherent. In fact, stylistic or even dramatic considerations may require the exact opposite—in the orchestration of spectral mixtures by melding of instrumental timbres, for example.

In contrast, clarity in information sonification is essential and rendering techniques that produce a kind of "sonic gumbo"[31] can be more successful.

[31] In gumbo cuisine, the ingredients are added—a little bit of this, a little of that—so that they do not meld together but remain sensorially distinct, yielding a 'rainbow' of flavors, aromas and textures rather than a uniform blend.

Consequently, sonifications in which the user-driven real-time exploration of datasets using dynamic scaling in multiple dimensions, perhaps with auditory beacons (Kramer 1994b), may not result in what is currently understood to be musically coherent sound streams. Even if listened to *as* music, information sonifications may provoke critical commentary about musical issues such as the appropriateness or formal incompleteness of the resulting sonic experience. Perhaps, as Paul Polansky suggested, the closest point of contact between such pragmatic data sonification and musical sonification is in compositions in which a composer intends to "manifest" mathematical or other formal processes (Polansky and Childs 2002). This "classical" algorithmic motivation is explicitly enunciated by Xenakis in his seminal book, *Formalized Music* ([1971] 1991), and many of the cultural concerns in his thesis defense (1985).

While numerous composers use mapping and other procedural techniques of one kind or another in their musical compositions, they are rarely interested in "featuring" the mapping explicitly. Nor do they use mapping in order to simplify the working process or to improve production efficiency, but so as to craft the emergence of musical forms. In order to gain a deeper insight into the way composers map conceptual gestures into musical gestures, Doornbusch (2002) surveyed a select few composers who employ the practice in algorithmic composition.

> I am not interested in projecting the properties of some mathematical model on to some audible phenomena in such a way that the model be recognized as the generator of some musical shape.

So, those interested in producing music of a certain complexity may shy away from simple mappings as they can be hard to integrate with other musical material of a substantial nature. On the other hand, as Larry Polansky explains:

> …the cognitive weight of complex mappings degenerates rapidly and nonlinearly such that beyond a certain point, everything is just 'complex'.

Even a suitably complex, structurally coherent mapping may not be musically sufficient if the composition relies on a (human) performer, as composer Richard Barrett (in ibid.) emphasizes:

> In a score one is always dealing with the relatively small number of parameters which can be recorded in notation, and which interact with an interpreter to produce a complex, 'living' result.

The importance of this embodied "living" aspect of music has often been forgotten, ignored, or even dismissed in many discussions of Western art music, including by some composers. While there are historical reasons and—consequences of doing so—such an approach to data sonification could have a major impact on the intelligibility of computer-rendered mapping-encoded artifacts.

1.11 Musical Notation as Representation

In Western art music, notation evolved, along with the notion of the *work*, from a performer's *aides-mémoire* to a tool of thought for defining works of increasingly abstract complexity (Goehr 1994). Notated scores came to be thought of as the encoded representation of sounds, even as a somewhat definitive objectification of a composer's thoughts. That we (at least in English) so frequently substitute the word 'note' for 'tone', and 'music' for 'score', exemplifies the strength of this conceptual elision. Indeed, in a number of intricately notated works of the twentieth century, it seems the performer is sometimes considered an unfortunate necessity. In others, notation functions as encapsulated stimuli by which the performers, as they attempt the impossible task of playing it "note-perfectly", enact a drama of physical and mental exertions.[32] Theodore Adorno noted a tendency to consider the bodily presence of the performer as a kind of contamination of musical experience, as a manifestation of a commodity fetishism where the "…immaculate performance … presents the work as already complete from the very first note. The performance sounds like its own phonograph record" (Adorno 1991).

Occidental art music today encompasses a wide range of motivations and listening practices, and reducing the intelligibility of such music to the conceptual level of scores and instruments enabled an unprecedented level of complexity. However, there is a growing recognition among music researchers, supported by a significant body of research in neuroscience,[33] that the conveyance of this complexity is reliant, at least to some extent, on embodied interpretation for effective communication (Goehr 1994). It was not until it was technically possible to construct musical compositions without the assistance of embodied interpreters that it was possible to meaningfully speculate on the extent to which a listener's perception of the structural characteristics of a piece of music are dependent on the sound-encoded gestures of performers, and not just the notated score. This has the unfortunate consequence that if sonifiers think of data as being the sonification equivalent of a parameterized musical score, and, following the path of least resistance, as most have been apt to do, use music composition software designed to produce abstract musical objects, their sonifications will lack the intelligence that is recognized as embodied in the (often micro-) gestures of musical performers (Worrall 2014).

This should act as a caution that, while adopting tools of one domain into another can be a very empowering, such adoption does not come value-free. If the intelligibility of much music is bound, not only to text, rhetoric, metaphor and formal devices such as phrase structure and the semantics of harmonic tension and resolution, but to the transmission through sound of the embodied foreknowledge of performers, in establishing the foundations for the practice of information

[32]This idea is integral to many of the works of a number of contemporary composers, including Mauricio Kagel, Luciano Berio, Brian Ferneyhough and Iannis Xenakis.

[33]Discussed in detail in Chaps. 3 and 4.

sonification, it is sensible to embrace approaches to forming sounds and their relationships that are supported, yet as unencumbered as possible, by the conceptual boundaries placed by tools for computer music-making as they currently exist. This, in turn, has the potential to enrich the practices for which the tools were originally meant.

Sounds and sonic structures demonstrate their weak proclivity to bind to casual inferences (Chion 2016) and strongly to metaphorical representations: From the rustle of dried leaves caused by escaping prey to the echoic resonances of a cathedral and a crowded street; from the phonetic structures of speech to word-painting in Renaissance madrigals; from musical rhetoric and Pastorals to instrumental expressions of affective states; from the turbulence of gas molecules to gravity waves and the folding and cracking of the earth's crust; from the movement of objects relative to each other to the flow of data through a network—sounds and sonic structures demonstrate homophonic[34] tendencies. With careful attention to details and their relationships to each other in context; to the isomorphic-heteromorphic bindings between sounds and their causes, sonification can render vibrant voices for unseeable things.

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[34]Homophones are similar sounds arising from different causes (for example, the sound of audience clapping and a crackling fire place). Homonyms are a special case: different words with the same pronunciation but different spellings and meanings, for example, "weather", "whether" and "wether".

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