

Theoretical outline of a hybrid musical system

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Abstract

Current approaches to musical research place a strong emphasis either on sound production - synthesis, algorithmic composition - or on cognitive models - information processing. As a way to start ploughing a common ground we outline a framework where musical structure is determined by the interaction of three inter-dependent aspects: sound system (physical), perceptual system (psychological) and social system. These are interlinked dynamically and their interaction provides a transformation of the state of each system. Information is defined by the range and rate of transformation of the elements in the physical system, being periodicity and entropy the two opposing factors that act on it. The probability that a specific information will be processed and transmitted by the perceptual system defines its state. We view each musical syntax as a sub-set of a greater system that includes the different forms of western music, defining observation in three levels: sound, syntax and morphology. The final output of the model - which depends on the probability that the combination of the present states will allow the processing of a given information - should provide a way to observe and compare the reaction of systems to the content of various musical phenomena.

Introduction

The approach taken in this paper follows a line that is represented by sporadic works that try to gather diversified fields in a common musical interdisciplinary ground (Birdlack, 1992; Boon et al, 1990; Eco, 1968; Georgescu & Georgescu, 1990; Moles, 1969; Malt, 1994). Although the need to define and formalize such a perspective has been pointed out by many researchers the difficulties encountered outnumber the useful tools available from each field (Bregman, 1990; Ferneda et al, 1994; Harnald, 1987; Parnutt, 1989; Sloboda, 1985). So two main reasons can be mentioned regarding the slow process towards unification: a tradition in the scientific and artistic community to separate and fragment areas of knowledge and the danger to transpose mechanically concepts developed in one field to another (Roederer, 1975; Vriend, 1981).

Our work addresses the problem of constructing a framework to deal with musical objects focusing on theoretical aspects and excluding actual implementation issues. This is based on the fact that the latter have already been treated in a large volume of publications and there is software available to observe the behavior of some parts of the proposed system - i.e. neural networks for pitch processing and perceptual tasks, simulation of a system behavior, mapping for the phase space, calculation of entropy, representation of signals in the time-frequency domain, correlation - (Arfib, 1991; Boon et al, 1990; LabVIEW, 1994; Matlab, 1994; Ramirez, 1985; Todd & Loy, 1991). Thus we discuss the most salient features and their theoretical implications in an effort to draw a global - but not complete - picture and to underline conceptual weakness of parts of a model whose details could be completed through future research.

Although analogies drawn from related fields have proven to be very useful for the understanding of music they cannot be taken as a ready-to-use tool (Roederer, 1975). Therefore when the concept of dynamical system is applied to music the characteristics of the system should be inferred from the behavior of real musical systems before we can establish any conclusion about the behavior of a musical system or any prediction on the results of a specific transformation. That is why we do not adhere to a one-sided physical or psychological description. Following the same line of thought, an early mathematical formalization may incur in simplifications that don't fit the complexity and unpredictability of musical phenomena (Knopoff & Hutchingson, 1981; Georgescu & Georgescu, 1990). We believe that it is a step that should eventually be taken when many of the posed (and also the ones not considered!) conceptual problems have been discussed and clarified.

At that stage, confirmation bias - the fact that the observer actively searches for evidence that supports his beliefs - and the complementarity principle - which states that observation depends on choices made by the observer, should have been introduced (Mitroff, 1974; Werner & Wells, 1990; Wolf, 1981). The whole musical process could be divided in three interlinked subsystems: sound system, perceptual system and social system. This subdivision comes out from the trends observed in musical research, where these areas can be clearly distinguished in relation to their methodology and object of study - i.e. signal processing, psychology of perception, developmental psychology (Deutsch, 1982; Flanagan, 1972; Hargreaves, 1948; Kubovy & Pomerantz, 1981; Oppenheim & Schafer, 1975; Pierce, 1983; Prince, 1972).

The sound system is defined as a time series - variations of a chosen variable as a function of time - that is, the unfolding of a sequence of acoustical signals (Boon et al, 1990). Information provided by the sound system is processed by a perceptual system whose dynamics are described by its states - or representations - which are modified by processes - or operations. Global constraints - established by the social system - set the range of possible perceptual states and thus the probability that the whole musical process will take place in a specified way.

Representation

From a philosophical point of view two main approaches can be traced regarding the process of knowledge acquisition. They are conceptually opposed but complementary in their application: elementism, that proposes an interaction of units or elements which combine in complexes to form perceptual objects, ideas, etc.; symbolism, that establishes direct acquisition of complex structures - symbols - which are related hierarchically to form new concepts or perceptual objects (Lischka, 1991; Marsden & Polpe, 1989; Massaro & Cowan, 1993; Rock, 1984; Wertheimer, 1974).

The existing wide spectrum of proposals on representation mechanisms range from logic-rules to complete absence of representation (Lischka, 1991; Pylyshyn, 1984; Suppes et al, 1994). No conclusive general results have been attained on the mental mechanisms activated by auditory stimuli, but some factors should be considered when treating specifically musical phenomena. We'll discuss some issues related to three perspectives: analytical, computational and psychological.

Psychological perspective

The traditional approaches in psychology of perception placed a strong emphasis on detection of thresholds (Zwicker et al, 1957; Luce & Clark, 1967; Roederer, 1974). Since the mid-sixties with the apparition of Signal Detection Theory a shift in paradigm called attention to the fact that the transmission and processing of information could be better understood by probability weights (McNicol, 1972; Garner, 1974; Green, 1988; Green, 1972; Green & Berg, 1991; Green & Swets, 1966; Green et al, 1984; Green et al, 1985; Lufti, 1992). Concepts as just-noticeable-difference were left aside (it is strange that in the music field this is still cited and used).

Springing from the pioneer works in Information Theory (Shannon, 1948; Coons & Kraehenbuel, 1958; Knopoff & Hutchingson, 1981; Knopoff & Hutchingson, 1983), but evolving to its own conceptual field, Information Processing (IP) has become one of the most influential paradigms in psychology (Massaro & Cowan, 1993; Suppes et al, 1994). The most general properties of IP are: *Informational description*: all environmental and mental processes can be described in terms of type and amount of information. *Recursive decomposition*: each stage of processing can be broken down into substages. *Flow continuity*: information is transmitted forward in time. *Flow dynamics*: each stage or operation takes time - there are no instantaneous mental processes. *Physical embodiment*: information processing occurs in a physical system. At last, coincidentally with the approach of this paper, IP establishes that information is embedded in states of a system - or representations -, and processes - or operations - are used to transform these representations.

An important distinction formulated by IP is that data should not be treated as information until it is processed by the receiver. From this point of view knowledge should be understood as information actually available by the individual and not the raw data present in the environment (Massaro & Cowan, 1993). A separation between physical (previous to mental processing) and psychological systems seems the simplest way to deal with this issue.

Rule-based models

Several limitations have been pointed out regarding the approaches based on linguistic analogy (Cook, 1994; Leman, 1989; Todd & Loy, 1991; Remez et al, 1994). Taking in count the characteristics of musical material, continuous representations which allow for decisions based on probability weights

approximate the uncertainty intrinsic of musical stimuli. This is excluded from rule-based approaches where decisions are taken in relation to pre-established constraints. Lischka (1991) points to the fact that continuous processes can hardly be explained by discrete categories and that combinatorial rules and various decision stages do not meet with the speed requirements of fast complex processes that occur in perception.

Hierarchical organization of layers does not consider interaction among interdependent factors such as macro and micro-structure in music (see Lerdahl, 1987; Lerdahl & Jackendoff, 1983; Bregman 1990; Deutsch, 1982b; Dowling & Harwood, 1986). The alternative approach of setting a system, where modification of any parameter at any level would cause a transformation of the system as a whole, seems to correspond better to real musical phenomena. A mental experiment would be to play a sonata by Mozart with a piano timbre and afterwards with white noise filtered to reproduce relative pitch variations - as in Hesse's experiment (1982). Where would harmonic functions, hierarchical structures, tonal closure, dissonance and consonance go? However its macro-structure would be kept exactly the same.

Parallel distributed processing models

Among the IP currents an approach that grew from a tentative to simulate the physiological structure of the brain and expanded to various applications is the parallel distributed processing or connectionist model. As with any present model several problems can be pointed out, nevertheless it is an expanding field that has implemented some useful tools (Rumelhart & McClelland, 1986; Todd & Loy, 1991).

Marsden & Pople (1989) describe it as consisting of a network of processing units, each producing a quantitative output which is a simple function of its input, again quantitative. Except where this output is the overall output of the model, it is routed to the input of other processing units. The arrangement and strength of the connections is contrived in such a way as to produce the appropriate overall output from the model, given appropriate input.

The drawback - and at the same time the advantage - of neural networks applied to auditory perceptual tasks is the possibility to predict an outcome - given the necessary conditions - without a pre-established model of auditory processing. The lack of explicit stages, not allowing time control of independent variables, the superpower of the model which permits different net structures to have the same outcome so alternative models cannot be verified and the difficulty to introduce distal causation (or correlations in events separated in time) are some of the weaknesses that have been pointed out (Laske, 1991; Massaro & Cowan, 1993). The pretension to validate the model on neurological bases suffers from some shortcomings:

1. Leman (1989) observes the lack of correspondence between reaction times in neuronal systems and a computer simulations. The basic computing elements of the brain operate in the range of a few milliseconds - a million times slower than current electronic devices. The reaction times of complex behaviors - such as hearing - are carried out in a few hundred time steps. He concludes that brain processes should be carried out by a massive parallel network of connected units. However this argument does not take in count the differences in reaction time that has been observed for different types of tasks (Pachella, 1974; Keller & Tróccoli, 1995; Dai & Green, 1993; Bernstein & Green, 1987b; Perfetti & Bell, 1983; Pitt & Crowder, 1992; Semal & Demany, 1991).

2. Wertheimer (1974) - supporting direct acquisition of complex structures - describes an experiment where micro-electrodes implanted in visual nerves of animals showed a group of nerve cells reacting to complex stimuli - the angle and direction of the movement of a line. On the other hand when specific parameters - as luminosity and wave length - were used no answer was elicited. Thus the scheme of input units that react to specific parameters can not be generalized.

Computational perspective

When we set to the task of analysing, transforming or producing musical information the first problem encountered is how to translate that information into a code that reflects the physical and perceptual characteristics of the signal. A digitized waveform only represents the variations of amplitude and frequency within a preassigned range and level of quantization (Garnett, 1991).

From a computational perspective information can be represented as plain data or as a knowledge system incorporating all characteristics that define that system, or an intermediate combination of this two possibilities. The issue here is the tradeoff between efficiency and easy of use. Following Garnett (1991) we would be talking about computational dynamics (the underlying operational flow of data and instructions) and computational semantics (the user interface). How this two levels relate has been minutely discussed in Representation of musical signals (DePoli et al, 1991). Three types of music signals have been proposed. Acoustic: time-pressure waveforms, analytic: such as FFT or autocorrelations, and parametric: derived from models such as linear predictive coding coefficients, synthesis parameters (Arfib, 1991; Flanagan, 1972; Roads, 1991).

The implementation of signals as a sequence of values indexed by positive integers - as in general signal processing - has proven to be the simplest and most efficient standard that can be adopted for their physical representation. The analytic transformation to a time-frequency representation can easily be done by means of Short Time Fourier Transform or Wavelet Transform (Arfib, 1991; Kronland-Martinet & Grossmann, 1991). Once in the frequency domain correlation can be applied to rate the signals in a predictability scale (Ramirez, 1985). High correlation would match most predictable states and low correlation would correspond to entropic states - as in random noise (Boon et al, 1990).

The advantage of using STFT and WT is that they allow for energy conservation, so they are reversible processes (Kronland-Martinet & Grossmann, 1991). This should be one of the important factors in deciding what representation to apply in a system where data is repeatedly transformed and handled through various stages. This simplifies controlling and testing outcomes of each stage for alternative models - e.g. a signal is transformed, modified and transformed back to its first representation to compare original and modified signal - .The approach adopted in the present paper proposes to deal with different types of data representation depending on the transformation being done. Thus data in the perceptual system should incorporate selective knowledge - an irreversible process - contrasting with the reversible processes of the sound system.

Musical analysis

The perspective that has the loosest level of formalization from the ones considered is musical analysis, including in this category analysis itself and related tasks as composing, performance, analysis-synthesis (Bent, 1987; Boulez, 1992; Karkoschka, 1972; Karkoschka, 1987; Menezes, 1987; Risset, 1991; Risset & Wessel, 1982; Schaeffer, 1993; Schoenberg, 1974; Wessel, 1979) - which imply a complex knowledge of musical structure that is in part intuitive.

Many criticisms have been pronounced in relation to this lack of formalization questioning the utility of this approach and trying to find a place where its production could be useful to research (DeLio, 1980; Demster & Brown, 1990; Kunst, 1987; Polansky & Bassein, 1992; Sloboda, 1985; Vriend, 1981). Cook's proposal of using music theory as a tool to open new musical frontiers appears to fit in the present panorama of research. We would like to add that where models can not be tested by other means, as a last resort we have our auditory system, plenty of biases and social conditionings but the only way to fully apprehend musical phenomena.

A hybrid musical system

Sound System

When music is considered as a time series the transformation of a variable in relation to time can be observed. This places a strong emphasis on the process itself but blurs our view of the structural regularities. That is, we can easily find correlations in events that are near in the time axis but distant events are difficult to compare. To facilitate observation, the scale - or kernel - of the representation is modified (Mozer, 1991). This allows us to look for regularities in the sound, syntax or morphology of a musical signal. If a musical work is understood as a system in equilibrium, its structure would be a time-invariant representation embodying all states. Their time history represents the dynamic process of the system. If we plot this process in a three dimensional graph, the evolution of the system is shown as a trajectory in the phase-space sustained by the x, y, z axes. This space equals the range of the system (Boon, 1990).

Nevertheless a conceptual differentiation is necessary when a shift of perspective occurs: the same phenomenon can be described as static (time-invariant) or dynamic (time-variant). A simple example would be a succession of five pitches which are played forwards and backwards. A static representation, as in Set Theory, would define a temporal space that is filled with five elements (Bent, 1987; Forte, 1970). A dynamic approach would represent the process used to order these elements.

The stability of the musical system is proportional to its entropy. Almost completely entropic systems are the most stable ones, so strong processes - highly energetic - are needed to disrupt their equilibrium - as it happens in stochastic music or random noise where foreign events can be introduced without great modification of the system's behavior. On the other hand a system with high periodicity will suffer a strong impact from a small perturbation - such is the case in Morton Feldman's music or in short repetitive patterns where any minor modification is easily detected. We can not draw final conclusions until experimental tests are run, but Georgescu & Georgescu's (1990) statement that "steady-state (structurally-stable) music is represented by works where stratified, deterministic, causal, memory-endowed dependences interact [...] as in a Mozart's sonata" does not seem very likely when compared to any Michael Jackson's hits.

Perceptual system

When the sound system is observed, an arbitrary portion of information is extracted so that there is a loss in the transmission between the actual physical system and its perceptual representation (Berstein & Green, 1987; Dowling, 1994; Durlach et al, 1986; Mason et al, 1984; Nielzen & Olsson, 1989; Yost & Watson, 1986). This loss can be represented by a dynamic information filter whose characteristic are defined by the state of the perceptual system.

Fusion or parsing can be thought as a high level process - that acts on other processes - . If we consider how psychoacoustical models process spectral information, clues such as harmonicity, synchronicity, spacing of components, modulation will define if the sound is perceived as a unit (Feth, 1974; Green, 1988; McAdams, 1982; Richards et al, 1989; Sano & Jenkins, 1991; Slawson, 1985; Terhardt et al, 1982; Vos & Rasch, 1982). Regarding musical syntax, pitch-height, pitch-class and interval representation - as in Bharucha's model (1991) - depend on synthetic or analytic hearing, in other words whether a fusion process is activated or not (Howe et al, 1993; Melara & Marks, 1990a; Melara & Marks, 1990b; Melara & Marks, 1990c; Singh, 1987).

At the time data reaches the information filter, it is parsed among available channels (Grossman, 1972). Depending on the range of the signal and its rate of transformation, the bandwidth and resolution of each channel is set. If their capacity is exceeded the fusion process is activated, then the number of channels is reduced and so is their resolution. The settings of the filter are stored in a buffer which accounts for the memory of the state of the perceptual system.

Social System

From a musical perspective the constrains imposed by the social system are mirrored in what a listener has as his musical background: all musical stimuli that he receives and how they are stored and used by him in specific tasks, i.e. producing and listening to sound (Hargreaves, 1948; Prince, 1972; Siegel, 1981; Sloboda, 1985). Environmental constrains are always present in production of music. Even when implementing automatic generation of random sound the limits are set by the sample space: only an infinite sample is completely random.

A variety of listening experiments has shown the influence of cultural context on the perception of music (Deliege, 1989; Jones, 1987; Krumhansl, 1990; Parncutt, 1989; Wolpert, 1990). Actually an important question in experimental research has been the problem of individualizing the variables that are acquired from interaction with the environment and the ones that are innate (Aiello, 1994; Deutsch, 1982; Krumhansl, 1990; Roederer, 1974). Although this differentiation is relevant, while enough data is not available the alternative approach of taking cultural constrains as given data may prove useful. The other aspect of the same problem is the interaction between environment and individual, thought as a feedback process where the action of each social component modifies the environment - as it is the case in musical production - . This has not yet been formalized either. Therefore we propose that the modifications infringed on the environment be incorporated as a feedback loop for each iteration among systems.

When analysing the behavior of a social system, the global features that characterize its dynamics are observed. Each specific event loses importance and the statistical distribution of a large number of events is focused. While in state of equilibrium the system favors the features that have the higher activation weights. When this features are outweighed by repeated exposure to contrasting stimuli, the equilibrium of the system is broken and a new state is reached.

Neural networks have the ability to learn patterns and features from a given set of musical examples (Todd & Loy, 1991). So the application of this knowledge is straight forward: feed the network with a relevant corpus of musical stimuli, extract the features that characterize them and use these features to set the limits of possible behaviors of the perceptual system.

Conclusion

We have only scratched the surface of the implications of a model that brings together physical, perceptual and social information to a musical framework. The division of the sound system in three levels - sound, syntax and morphology - provides a way to treat different types of information without fragmenting the musical structure. Entropy and periodicity used to define the stability of the sound system allow for predictions on its behavior. Fusion-parsing as a high level process acting on information selection simplifies the structure of perceptual mechanisms. Constrains defined by the social system contextualize the musical process in a specific environment. Further development of this line of research should introduce attractors and control parameters for

each system and quantification devices to arrive to a mathematical formulation that does not exclude uncertainty and fuzziness.

The purpose of this exposition was just to light the fire of a discussion that's far from ended, we hope that many ideas will come to stir this musical system's equilibrium. To give an overall view as to how this system could be put to work, we propose a rough-draft of ordered procedures, with the reminder that feedback and crossed connections are missing.

Procedure

Sound System

Establish a kernel [sound - syntax - morphology].

Sound.

Establish domain [time - frequency].

Apply transformation [correlation].

Find the range [minimum - maximum].

Plot a static representation [system].

Define sub-range. (In case of processes under perceptual threshold, phase - in periodic signals - could be a parameter used to define time range).

Plot a time-varying representation [states].

Find the process underlying the dynamics of the system.

Syntax.

Feed signal 1.

Establish domain [duration - intensity - pitch].

Apply correlation within.

Find range.

Plot static representation [system].

Define sub-range [perceptive unit].

Plot a time-varying representation [states].

Find the process underlying the dynamics of the system.

Feed signal 2.

Establish domain [duration - intensity - pitch].

Apply correlation within.

Find range.

Plot static representation [system].

Define sub-range [perceptive unit].

Plot a time-varying representation [states].

Find the process underlying the dynamics of the system.

Feed signals 1 and 2.

Apply correlation between.

Find range.

Plot static representation.

Define sub-range [perceptive unit].

Plot a time-varying representation [states].

Find the process underlying the dynamics of the system.

Morphology.

Establish domain [information distribution (range and rate of transformation)].

Apply correlation [sound: time - frequency][syntax: duration - pitch - intensity].

Compare morphologies.

Perceptual system

Establish variable [sound - syntax - morphology].

Observe Garner effect - interactions.

Input stage [temporal clues - spectral clues].

Transformational stage [fusion - parsing][fit pattern][map to representation] [dynamic information filter (buffer)].

Output stage [feedback][fuzzy decodification].
Compare input and output.

Social System

Input stage [dominating corpus of music].
Transformation stage [statistical weight to strong activations].
Output stage [relevant features][constrains to perceptual system].

References

- Aiello, R. (Ed.) (1994). *Musical perceptions*. New York: Oxford University Press.
- Arfib, D. (1991). Analysis, transformation, and resynthesis of musical sounds with the help of a time-frequency representation, *Representation of Musical Signals*. Cambridge, MA: MIT Press.
- Bharucha, J.J. (1991). Pitch, harmony, and neural nets: a psychological perspective, *Music and Connectionism*. Cambridge, MA: MIT Press.
- Bent, I. (1987). *Analysis*. New York: London.
- Berg, B. G. & Green, D. M. (1990). Spectral weights in profile listening. *Journal of the Acoustical Society of America*, 88, 758-766.
- Bernstein, L. R. & Green, D. M. (1987a). The profile analysis bandwidth. *Journal of the Acoustical Society of America*, 81, 1888-1895.
- Bernstein, L. R. & Green, D. M. (1987b). Detection of simple and complex changes of spectral shape. *Journal of the Acoustical Society of America*, 82, 1587-1592.
- Bidlack, R. (1992). Chaotic systems as simple (but complex) compositional algorithms. *Computer Music Journal*, 16 (3), 33-47.
- Boon, J.P., Noullez, A. & Mommen, C. (1990). Complex dynamics and musical structure. *Interface*, 19, 3-14.
- Boulez, P. (1992). *Hacia una estética musical*. Caracas, Venezuela: Monte Ávila Editores.
- Bregman, A. S. (1990). *Auditory Scene Analysis: the perceptual organization of sound*. Cambridge, MA: MIT Press.
- Cook, N. (1994). Perception: a perspective from music theory, *Musical Perceptions*. New York: Oxford University Press.
- Coons, E. & Kraehenbuehl, D. (1958). Information as a measure of structure in music. *Journal of Music Theory*, 2, 127-161.
- Dai, H. & Green, D. M. (1993). Discrimination of spectral shape as a function of stimulus duration. *Journal of the Acoustical Society of America*, 93 (2), 957-965.
- Dalhaus, C. (1975). Some models of unity in musical form. *Journal of Music Theory*, 19, 1, 2-30.
- DePoli, G., Piccialli, A., Roads, C. (1991). *Representation of musical signals*. Cambridge, MA: MIT Press.
- Deliège, I. (1989). A perceptual approach to contemporary musical form. *Contemporary Music Review* 4, 213-230.
- DeLio, T. (1980). Iannis Xenakis' Nomos Alpha: the dialectics of structure and materials. *Journal of Music Theory* 24.1, 63-95.
- Demster, D. & Brown, M. (1990). Evaluating musical analyses and theories: five perspectives. *Journal of Music Theory*, 34.2, 247-279.
- Deutsch, D. (Ed.) (1982a). *The psychology of music*. New York: Academic Press.
- Deutsch, D. (1982b). Organizational processes in music, *Musical Mind and Brain*. New York: Plenum Press.
- Dodge, C. & Jerse, T. A. (1985). *Computer Music*. New York: Schirmer Books.
- Dowling, W. J. (1994). Melodic contour in hearing and remembering melodies, *Musical Perceptions*. New York: Oxford University Press.
- Dowling, W. J. & Harwood, D. L. (1986). *Musical Cognition*. Orlando, FL: Academic Press.
- Durlach, N. I., Braida, L. D., and Ito, Y. (1986). Toward a model for discrimination of broadband signals. *Journal of the Acoustical Society of America* 80, 63-72.
- Eco, U. (1968). *Obra Aberta*. São Paulo: Editora Perspectiva.
- Ferneda, E., Silva, C.A.P. da, Teixeira, L.M., Menezes Silva, H. de, (1994). A system for aiding discovery in musical analysis, *Anais do I simpósio brasileiro de computação e música*. Belo Horizonte, MG: Maurício Loureiro.
- Feth, L. L. (1974). Frequency discrimination of complex periodic tones. *Perception & Psychophysics*, 15, 375-378.
- Flanagan, J. L. (1972). *Speech analysis, synthesis and perception*. New Jersey, Murray Hill: Bell Laboratories.
- Forté, A. (1970). *The structure of atonal music*. New Haven, CT: Yale University Press.
- Garner, W. R. (1974). *The processing of information and structure*. New York: Wiley.
- Garnett, G.E. (1991). Music, signals and representations: a survey, *Representation of Musical Signals*. Cambridge, MA: MIT Press.
- Geary, J. M. (1980). Consonance and dissonance of pairs of inharmonic sounds. *Journal of the Acoustical Society of America*, 67, 1785-1789.
- Georgescu, C. & Georgescu, M. (1990). A system approach to music. *Interface*, 19, 15-52.
- Green, D. M. & Berg, B. G. (1991). Spectral weights and profile bowl. *Quarterly Journal Experimental Psychology*, 43A, 449-458.
- Green, D. M. & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.
- Green, D. M. (1988). *Profile Analysis: Auditory Intensity Discrimination*. New York: Oxford University Press.
- Green, D. M., Mason, C. R., & Kidd, G., Jr. (1984). Profile analysis: critical bands and duration. *Journal of the Acoustical Society of America*, 75, 1163-1167.
- Green, D. M. & Mason, C. R. (1985). Auditory profile analysis: frequency, phase and Weber's law. *Journal of the Acoustical Society of America*, 77, 1155-1161.
- Green, D. M. (1992). The number of components in profile analysis tasks. *Journal of the Acoustical Society of America*, 91, 1616-1623.
- Grey, J. M. & Gordon, J. W. (1978). Perceptual effects of the spectral modifications of musical timbres. *Journal of the Acoustical Society of America*, 63, 1493-1500.
- Grey, J. M. (1977). Multidimensional perceptual scaling of musical timbres. *Journal of the Acoustical Society of America*, 61, 1270-1277.
- Grey, J. M. (1978). Timbre discrimination in musical patterns. *Journal of the Acoustical Society of America*, 64, 467-472.
- Grossman, E.E. (1972). Signal detection theory applications to a developmental analysis of auditory intensity selectivity. *Doctoral Thesis in Psychology*. Fayetteville, AR: University of Arkansas.
- Hargreaves, D. (1948). *The developmental psychology of music*. Cambridge: Cambridge University Press.
- Harnald, S. (Ed.) (1987). *Categorical perception: the groundwork of cognition*. Cambridge: Cambridge University Press.
- Helmholtz, H. von (1885). *On the Sensations of Tone*. London: Longmans.
- Hesse, H. P. (1982). The judgement of musical intervals, *Musical Mind and Brain*. New York: Plenum Press.
- Howe, M. L., Rabinowitz, F. M., Grant, M. J. (1993). On measuring (in)dependence of cognitive processes. *Psychological Review*, 100 (4), 737-747.
- Iverson, P. & Krumhansl, C. L. (1991). Measuring similarity of musical timbres. *Journal of the Acoustical Society of America*, 89 (2), 1988.
- Jones, M. R. (1987). Dynamic pattern structure in music: recent theory and research. *Perception & Psychophysics*, 41, 621-634.
- Karkoschka, E. (1972). *Notations in new music*. London: Universal Edition.
- Karkoschka, E. (1987). Analysis of new music. *Interface* 16, 13-21.
- Keller, D. & Tróccoli, B.T. (1995). Percepção auditiva: aspectos da interação entre psicologia e música, *Anais do II congresso de ciências humanas e artes*. Uberlândia: Universidade Federal de Uberlândia.
- Knopoff, L. & Hutchingson, W. (1981). Information theory for musical continua. *Journal of Music Theory* 25.1 17-43.
- Knopoff, L. & Hutchingson, W. (1983). Entropy as a measure of style: the influence of sample length. *Journal of Music Theory* 27.1, 75-97.
- Kronland-Martinet, R. & Grossmann, A. (1991). Application of time-frequency and time-scale methods (wavelet transforms) to the analysis, synthesis and transformation of natural sounds, *Representation of Musical Signals*. Cambridge, MA: MIT Press.
- Krumhansl, C. L. (1990). *Cognitive foundations of musical pitch*. New York: Oxford University Press.
- Kubovy, M., & Pomerantz, J. R. (Eds.) (1981). *Perceptual Organization*. New York, Hillsdale: Erlbaum.
- Kunst, J. (1987). Remarks on analysis. *Interface*, 16, 1-11.
- LabVIEW (1994). *Graphical Programming for Instrumentation*. Austin, TX: National Instruments Corporation.
- Laske, O. (1991). Letter: connectionist composition, *Music and connectionism*. Cambridge, MA: MIT Press.
- Leman, M. (1989). Symbolic and subsymbolic information processing in models of musical communication and cognition. *Interface*, 18, 141-160.
- Lerdahl, F. (1987). Timbral hierarchies. *Contemporary Music Review* 2, 135-60.
- Lerdahl, F. & Jackendoff, R. (1983). *A generative theory of tonal music*. Cambridge, MA: MIT Press.
- Lischka, C. (1991). Understanding music cognition: a connectionist view, *Representations of Musical Signals*. Cambridge, MA: MIT Press.
- Luce, D. & Clark, M. Jr. (1967). Physical correlates of brass-instrument tones. *Journal of the Acoustical Society of America*, 42 (6), 1232-1243.

- Lufti, R. A. (1992). Informational processing of complex sound. III: interference. *Journal of the Acoustical Society of America*, 91 (6), 3391-3401.
- Malt, M. (1994). Modelos matemáticos e composição assistida por computador, sistemas estocásticos e sistemas caóticos, *Anais do I simpósio brasileiro de computação e música*. Belo Horizonte, MG: Maurício Loureiro.
- Marsden, A. & Pople, A. (1989). Towards a connected distributed model of musical listening. *Interface*, 18, 61-72.
- Mason, C. R., Kidd, G., Jr., Hanna, T. & Green, D. M. (1984). Profile analysis and level variation. *Hearing Research*, 13, 269-275.
- Massaro, D. W. & Cowan, N. (1993). Information processing models: microscopes of the mind. *Annual Review of Psychology*, 44, 383-425.
- Matlab (1992). *MATLAB User's Guide*. New York: Mathworks, Inc.
- McAdams, S. (1982). Spectral fusion and the creation of auditory images. *Music Mind and Brain*. New York: Plenum Press.
- McNicol, D. (1972). *A primer of signal detection theory*. London: George Allen & Unwin Ltd.
- Melara, R. D. & Marks, L. E. (1990a). HARD and SOFT interacting dimensions: differential effects of dual context on classification. *Perception & Psychophysics*, 47, 307-325.
- Melara, R. D. & Marks, L. E. (1990b). Interaction among auditory dimensions: timbre, pitch, and loudness. *Perception & Psychophysics*, 48, 169-178.
- Melara, R. D. & Marks, L.E. (1990c). Perceptual primacy of dimensions: support for a model of dimensional interaction. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 398-414.
- Menezes Filho, F. (1987). *Apoteose de Schoenberg*. São Paulo: Nova Stella/EdUSP.
- Mitroff, I.I. (1974). *The subjective side of science*. Amsterdam: Elsevier.
- Moles, A. (1969). *Teoria da informação e percepção estética*. Rio de Janeiro: Tempo Brasileiro.
- Mozer, M.C. (1991). Connectionist music composition based on melodic, stylistic, and psychophysical constraints. *Music and connectionism*. Cambridge, MA: MIT Press.
- Nielzen, S., & Olsson, S. (Eds.) (1989). *Structure and perception of electroacoustic sound and music*. Amsterdam: Elsevier.
- Oppeinheim, A. & Schafer, R. (1975). *Digital signal processing*. Englewood cliffs: Prentice-Hall.
- Pachella, R. G. (1974). The interpretation of reaction time in information-processing research. *Human information processing: tutorials in performance and cognition*. Kantowitz, B.H. (Ed.). Hillsdale, New Jersey: Erlbaum.
- Parncutt, R. (1989). *Harmony: a psychoacoustic approach*. Berlin: Springer-Verlag.
- Perfetti, C. A. & Bell, L. C. (1991). Phoneme activation during first 40 ms. of word identification: evidence from backward masking and priming. *Journal of Memory and Language*, 30, 473-485.
- Pierce, J. (1983). *Musical Sound*. New York: Scientific American Books.
- Pitt, M. A. & Crowder, R. G. (1992). The role of spectral and dynamic cues in imagery for musical timbre. *Journal of Experimental Psychology: Human Perception and Performance*, 18 (3), 728-738.
- Polansky, L. & Bassein, R. (1992). Possible and impossible melody: formal aspects of contour. *Journal of Music Theory*, 36.2, 259-284.
- Prince, W.F. (1972). A paradigm for research on music listening. *Journal of Research in Music Education*, 28, 445-455.
- Pylshyn, Z. (1984). *Computation and cognition*. Cambridge, MA: MIT Press.
- Ramirez, R.W. (1985). *The FFT. Fundamentals and concepts*. New Jersey: Prentice Hall, Englewood Cliffs.
- Remez, E.R., Rubin, P.E., Berns, S.M., Pardo, J.S., Lang, J.M. (1994). On the perceptual organization of speech. *Psychological Review*, 101 (1), 129-156.
- Richards, V. M., Onsan, Z. A. & Green, D. M. (1989). Auditory profile analysis: potential pitch cues. *Hearing Research*, 39, 27-36.
- Risset, J.C. & Mathews, M.V. (1969). Analysis of musical instrument tones. *Physics Today*, 22 (2), 23-30.
- Risset, J.C. (1991). Timbre analysis by synthesis: representations, imitations and variants for musical composition. *Representation of musical signals*. Cambridge, MA: MIT Press.
- Roads, C. (1991). Asynchronous granular synthesis. *Representation of musical signals*. Cambridge, MA: MIT Press.
- Rock, I. (1984). *Perception*. New York: Scientific American Books.
- Roederer, J.G. (1975). *Introduction to the physics and psychophysics of music*. New York: Springer-Verlag.
- Rumelhart, D.E. & McClelland, J.L. (1986). *Parallel distributed processing*. Cambridge, MA: MIT Press. Vol.1, Vol.2.
- Sano, H. & Jenkins, B.K. (1991). A neural network model for pitch perception. *Music and connectionism*. Cambridge, MA: MIT Press.

- Schaeffer, P. (1993). *Tratado dos Objetos Musicais*. Brasília: Edunb.
- Schoenberg, A. (1974). *Tratado de Armonia*. Madrid: Real Musical.
- Semal, C. & Demany, L. (1991). Dissociation of pitch from timbre in auditory short-term memory. *Journal of the Acoustical Society of America* 89, 2404-2410.
- Singh, P. G. (1987). Perceptual organization of complex tone sequences: a tradeoff between pitch and timbre?. *Journal of the Acoustical Society of America*, 82, 886-899.
- Siegel, J. A. (1981). Culturally Defined Learning Experience. *Documentary Report of the Ann Arbor Symposium: Applications of Psychology to the Teaching and Learning of Music*. Reston: Music Educator National Conference.
- Slawson, W. (1985). *Sound color*. Berkeley, CA: University of California Press.
- Sloboda, J. A. (Ed.) (1985). *Generative processes in music: the psychology of performance, improvisation and composition*. New York: Oxford University Press.
- Suppes, P., Pavel, M., Falmagne, J.C. (1994). Representations and models in psychology. *Annual Review of Psychology*, 45, 517-544.
- Terhardt, E., Stoll, G., & Seewan, M. (1982). Pitch of complex signals according to virtual-pitch theory: tests, examples, and predictions. *Journal of the Acoustical Society of America*, 71, 671-678.
- Todd, P. M. & Loy, G. D. (Eds.) (1991). *Music and connectionism*. Cambridge, MA: MIT Press.
- Vos, J. and Rasch, R. (1982). The perceptual onset of musical tones. *Music Mind and Brain*. New York: Plenum Press.
- Vriend, J. (1981). "Nomos Alpha" for violoncello solo - Xenakis 1966 - analysis and comments. *Interface*, 10, 15-82.
- Wenner, A.M. & Wells, P.H. (1990). *Anatomy of a controversy: the question of a "language" among bees*. New York: Columbia University Press.
- Wertheimer, M. (1974). The problem of perceptual structure. *Human information-processing: tutorials in performance and cognition*. Kantowitz, B.H. (Ed.). Hillsdale, New Jersey: Erlbaum.
- Wessel, D. (1979). Timbre space as a musical control structure. *Computer Music Journal*, 3, 45-52.
- Wolf, F.A. (1981). *Taking the quantum leap*. San Francisco: Harper & Row.
- Wolpert, R. (1990). Recognition of melody, harmonic accompaniment and instrumentation. *Music Perception*, 7, 253-258.
- Yost, W. A. & Watson, C. S. (Eds.) (1986). *Auditory processing of complex sounds*. New York, Hillsdale: Erlbaum.
- Zwicker, E., Flottorp, C. & Stevens, S. S. (1957). Critical bandwidth in loudness summation. *Journal of the Acoustical Society of America*, 29, 548-557.

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