Jean-Claude RISSET
Laboratoire de Mécanique et d'Acoustique, CNRS, Marseille
jcrisset@lma.cnrs-mrs.fr

THE PERCEPTION OF MUSICAL SOUND

WHY FOCUS ON THE PERCEPTION OF MUSICAL SOUND?

The considerable development of science and technology in the XXth century has put many new tools at the disposal of the musican -intellectual tools as well as material tools. Sounds - and images as well - can now be synthesized. The process of synthesis is completely unprecedented : visual and auditory signals can be calculated altogether. This brings considerable changes not only to the generation of images and sounds - their morphogenesis -, but also to the way they can be represented, stored, reproduced, distributed. The programming of artistic media implies language, formalism, computation : it affects our conceptions and our notion of reality, and it alters the reception and the perception of art as well as the processes of creation.

Art is received and *perceived* through the senses. When the artist constructs a work of art, he deals with the physical world, using tools that can be elaborate - brushes, paint, carving tools, music notation, musical instruments, architectural blueprints : but most of the time the sensory effect of these tools can be appreciated at once.

Structures can often be defined in a rigorous, objective way, for instance in terms of mathematical descriptions. However what counts in art is not the objective structure - *per se* - but the structure *in us,* as we experience it through our senses[1]. Ancient Greek architects were said to correct geometry to satisfy our senses. The idiosyncrasies of perception can be illustrated by some simple visual illusions such as the Hering illusions (where objectively straight vertical lines seem twisted) and the Muller-Lyer illusion (where segments of equal length appear quite unequal).

It is often a delusion to rely on a physical description for predicting the appearance or the effect of a visual or an auditory scene realized with elaborate technical processes : one should be aware of the complexity of the relation between the physics of the signal and the way it is perceived. If you take the case of light, the color of a "pure" light depends upon its wavelength : but the same color can also be evoked by adding an appropriate mix of two pure lights, each of which in isolation would evoke different colors.

In the case of music, our understanding of the perception of musical sound has been considerabled augmented and changed by the exploration of the resources of synthesis. Auditory perception is more complex than one believed, and it is essential to understand its specificities when one manufacture musical sounds by synthesis.

[1] A distinction proposed by Jacques Mandelbrojt.

OBJECTIVE AND PERCEIVED RELATIONS IN SOUND AND MUSIC

The crucial issue of structures *in us* versus *per se* has been present in music since Pythagoras and Aristoxenus. According to Pythagoras, numbers rule the world - the privileged intervals of harmony as well as the motions of the celestial spheres. The ratio 3/2 between the frequency of two tones determines an interval of a fifth between them. But Aristoxenus argued that the justification of music lies in the ear and not in a mathematical rationale. Who is right?

It is easy to check that a ratio of 3/2 idoes not always sounds like a fifth. Above 5000 Hz or so, the ear looses its capacity to make a precise evaluation of intervals (in fact, the high range of pitched instruments stops below 5000 Hz). This breakdown in the capacity of evaluating intervals can be explained by physiology, but it implies that one should be cautious : the frequency ratios do not always give the expected effects.

"ELECTRIC" SOUND AND ITS CHALLENGES : OBJECTIVE AND PERCEIVED STRUCTURES

With traditional instruments, the composer specifies scores, instructions on how to play the instruments, using a repertory of symbols that refer to the sounds which the instruments can play, and which vary in terms of parameters such as pitch, time of attack, duration. The relation between the musical symbols and their sensory effects is clear and intuitive, and indeed the composer can resort to "inner listening", he can form an idea of the music by looking at the score. In the XXth century, most composers using the sonic vocabulary of instrumental sounds (such as Stravinsky, Schoenberg, Boulez) have concentrated their effort of innovation on the "grammar" of music, the syntax governing the assembly of symbols constituting the score.

On the other hand, some composers have been intent on renewing the vocabulary of music. Varèse insisted that new sonic materials would permit and even call for novel architectures. It would not be appropriate to impose on these new material grammatical rules developed in other circumstances.

When the mediation of technology develops, the relation between action and effect often gets less intuitive and more obscure. Since 1875, two inventions have gradually but deeply changed our relation with sounds. The invention of recording has turned ephemeral sounds into objects that can be reproduced in the absence of their mechanical cause, scrutinized, transformed in unprecedented ways - thus the mapping of time onto space makes it possible to alter the temporal aspects of sounds, for instance to reverse sound in time. The intrusion of electricity into the sonic domain has open a wide new potential for the creation and processing of sounds : novel possibilities to physically produce and modify sounds have been continuously developing through the successive "ages" of electrical technology - electrodynamic; electronic; digital; and networked.

AUDITORY PERCEPTION : STRUCTURES PER SE / IN US, ILLUSIONS

Music is meant to be heard. What counts in music is not the relation between the physical parameters of sounds, the parameters that computer synthesis directly controls and manipulates, but the relation we perceive when we listen to them. Hence, to take advantage of the possibilities of the computer for making music, it becomes necessary to understand how the physical relations set between sounds translate into audible relations - how structures "per se" determine structures "in us".

Even at the level of relatively simple and isolated sounds, the exploration of synthesis has forced musicians - and scientists - to admit that the way they are aurally perceived could sometimes be obscure and quite unintuitive, and that a given physical structure can be completely altered by perception.

For instance, complex periodic tones with the same frequency and spectrum but different phases sound the same to the ear, although the sound waves look extremely different. Drawing sound waves can be misleading.

Hearing has idiosyncrasies which one must take in consideration in one's compositional project - if one does not want the intent would be distorded by its incarnation into sound. A well-known composer insisted he was only concerned with the relations between tones, as specificied in the score : he thought he would specify a pitch cluster with frequencies 125, 128, 131, etc, up to 158 Hz : but the resulting effect was that of singe sound repeated three times per second. This unintuitive effect corresponds to a pattern of beats, illustrated by the mathematical identity :

$$\cos 2\pi f_1 t + \cos 2\pi f_2 t = 2\cos\{2\pi(f_1+f_2)t/2\}\cos\{2\pi(f_1-f_2)t/2\}$$

(adding more equally-spaced lines produce the same effect, but it increases the selectivity) but this identity does not tell us whether we shall hear two tones, as suggested by the left part of the identity, or one single tone, as the right part would suggest. It is the ear and brain which decides that if f_1 and f_2 are close, it hears the sum as beats, not as clusters.

I produce a surprising illusion : a sound that seems to go down when the frequency of its components are doubled. A tone can seem to do down in pitch by about one semi-tone while it physically goes up one octave (cf. Risset, 1986)[2]. One can form an idea of the "trick" by playing together on a piano a low C, a C# one octave higher, a D one octave higher, and a D# one octave higher, and then transposing all those tones together up one octave.

I have produced a similar illusion with rhythm : a pattern of beats can appear to slow down when one doubles the speed of the tape on which it is recorded.

As Purkinje said, illusions are errors of the senses but truths of perception. Visual illusions have been known for a long time : it was easy to contrive the elements of a visual figure by simply drawing it. But one does not control directly the physical parameters of acoustic sounds : many auditory illusions were only demonstrated with computer-synthesized sounds, which can be arbitrarily configured with great precision.

---

[2] One might describe this effect as a kind of stroboscopy or heterodyning due to the interaction between two intervals : the octave interval, very conspicuous for the ear (to the extent that notes octaves apart are given the same names - A, B, C ...) and the interval of self-similarity within the tones - here one octave and one semi-tone.

One can take advantage of auditory illusions in musical compositions. John Chowning's research elucidated cues for auditory perspective and the sensation of distance; simulating the Döppler effect, he could suggest fast movements of illusory sound sources. This provided insight as well as new possibilities, as witnessed by his work T*urenas* (1973), a milestone of cinetic music: sound sources seem to swiftly whirlwind around the listener, while all sounds are emitted for four loudspeakers. The illusory motions are computed with mathematical precision : they can be as vivid as visual trajectories.

Musical pitch, the subjective attribute that varies when a tone goes up or down, is **not** isomorphous to objective frequency (or its logarithm). While frequency variations can be represented along one axis, the variations of pitch, as experienced by the listener, are better represented along a spiral, which figures both a circular component (chroma) as well as a linear one (tone height). This pitch spiral can be made to collapse into a circle - which is illustrated by the cyclic character of the musical nomenclature (la si do ré mi fa sol la/A B C D E F G A). This collapse is favored when pitch is reduced to pitch class - when tone components are octave-related, displaying an instance of a fractal structure. Then a tone can glide up or down indefinitely, along the circle of pitch, just like the Fraser curves that look like spirals - Fraser's spirals - consists in fact of concentric circles.

Shepard and I have developed similar illusions or paradoxes for sounds made up of only octave components - which is a simple fractal structure.

The pitch spiral can also be altered so that a descending scale will lead to a final pitch much higher than where it started, like in the well-known Escher's water stream that flows down to a higher point. Similar paradoxical effects can be demonstrated for rhythm. I have used auditory illusions in several compositions, both computer-synthesized and instrumental. György Ligeti has used pitch and rhythm illusions in his piano *Etudes*.

There is the saying "Beauty is in the eye of the beholder". What matters in music is not intrinsic complexity, but the complexity we perceive, complexity in us. Some people claim that acoustic sounds will always be more complex than computer-generated ones. This is not true of objective complexity : a signal made up of samples independently chosen at random has maximal complexity, but we cannot cope with that richness of information - white noise sounds undifferentiated.

EVOLUTION AND OUR VIEW OF THE WORLD

Perception seems to have weird idiosyncrasies. Yet it is by no means arbitrary : its processes can be best understood by considering that the senses are not systems that scale the physical parameters of the sensory signals, but rather perceptual systems designed and equiped in specific ways so as to extract from those sensory signals significant information about the outside world that can help survival. These systems have developed under the pressure of evolution : the features effectively favoring survival have been reinforced. This view of perception, sometimes termed ecologic or functional, has been initially proposed by James J. Gibson. It has been elaborated since

1970 by other researchers, specially Bregman, Kubovy, Shepard, Chowning, Wessel, McAdams and myself for the case of hearing.

Evolution has played a great role in shaping the modalities of the perceptual organization performed by our senses. Hearing is good at detecting the origin and cause of sound. We have elaborate mechanisms to unravel a cacophony of different sounds, to sort out frequency components and to attach different components to different sources. We enjoy the gratuitous use of these capacities for our jubilation when we listen to complex music. But we have evolved in a mechanical world, and our strategies of "source-bonding" - detecting the source and the causality of a sound - are affective if it this sound was generated acoustically : but our interpretations remain unduly the same with electroacoustic signals, produced according to quite different logics. A signal with a sharp attack and a resonant decay will be heard as percussive, even if it is computed, without any percussion intervening in the process. This is a limitation for the composer using synthetic sounds : they may not sound as novel or unfamiliar that he or she might want, even though their physical structure is unprecedented.

Some features of the perceptual organization seems to be innate, but they only mature through practice - we can even be trained out of them. This seems to be the case for absolute pich - i.e. the capacity to recognize the note played without being given a reference tone.

In fact perception of music relates to visual perception and to linguistic processes, which have been studied more extensively.

PERCEPTUAL PROCESSES (GESTALT REVISITED)

Studying vision, the Gestalt psychologists had explicited law or principles of perception in the early XXth century. Recent research has shown that similar principles hold for hearing: they help the listener to make sense out of complex sonic signals.

Thus Diana Deutsch has shown that hearing tends to group elements together according to the organisation principles that had been described by Wertheimer in 1923 : grouping is favored by the proximity of elements, by their similarity; it also occurs so as to maintain continuity or "closure" (that is to form delimited units)[3]. Grouping coordinates isolated objects into melodic lines or rhythms. Time and pitch are important parameters for coordination.

Albert Bregman has gathered evidence that hearing performs efficient "scene analysis" : it can unravel a magma of frequency .components and treat certain groups of them as separate entities, each of which could be assigned to a sound source.

In this respect, two mechanisms of perceptual organization play a useful role.

One is the so-called stream segregation : a stream of successive tones can split into two streams that are perceived as different lines. The grouping into one line can occur on the

---

[3] Fig. I 45 shows that closure helps recognize the word "MUSIC" : the context and the assumed regularity incline one to envision the separate elements as a whole. This phenomenon relates to the capacity of hearing to prolongate melodic lines while they are masked by a noise.

basis of pitch proximity.: but grouping can also be based on briliance, as shown by Wessel. Segregation can also be caused by spatial separation of the sound sources, which indicate that spatial control can play a structural role, despite the statements of Pierre Boulez to the contrary. Rhythm can be perceived within one segregated line, but temporal coordination is lost between two segregated lines : this underlies my rhythmic paradox of beats that seem to slow down when you double the speed of the tape recorder.

John Chowning has demonstrated that the ear uses common fate, still another important principle for grouping, to distinguish between different sounds with frequency components that coïncide : the ear attaches together all the components that have synchronous microvariations.

Perceptual effects such as the above have often been discovered and illustrated by musicians, as we shall see below for Chowning's work *Phone*. Such idiosyncratic mechanisms underlie our perceptual organization - many are present at birth : it is on top of a ground of basic inborn capabilities filtered through evolution that learning takes place (for instance the pitch quantization imposed by musical scales is learned during chilhood). These mechanisms are involved in the perception of music, for instance our capacity to deal with polyphony, to hear out various timbres or various parts.

MATERIALS, ARCHITECTURE - WORKING WITH VOCABULARY RATHER THAN GRAMMAR : NEW POSSIBILITIES

Throughout the XXth century, composers were intent on innovation. Some tried to promote new grammars, new compositional methods - like new modality, atonality, serialism, stochastic music. But others focused on the vocabulary of the music, on the sound itself. Varèse was the pionneer for this trend. He insisted on the need to take advantage of science and technology to renovate the sonic material : he claimed that new materials would permit novel architectures. Indeed the mastery of electric processing of sound logically lead to musique concrète, electronic music and computer music.

Computer synthesis was developed from 1957 by Max Mathews, with the help of others, specially Newman Guttman and John Pierce. Pierce invented communication satellites and many other things : he also contributed to starting computer music and he protected it as research director at Bell Laboratories.

Synthesis opened new territories. It made possible to extend the compositional control at the level of sound, to unite the organization of the microstructure and the macrostructure - to compose the sound itself, not merely composing with sounds : instead of arranging sounds in time, one can play with time within the sound.

Since auditory perception can be so unpredictable, these possibilities had to be conquered through research. For instance even the mere imitation of instruments was harder than one thought. The interest of synthesis is not mere imitation, but rather to offer a variety of sonic material including and going beyond traditional instruments.

The model of a quasi-periodic tones with an amplitude envelope and a fixed spectrum does not work for certain instruments, such as the trumpet. or the bowed strings. One had to construct more complex models. Additive synthesis can give good results provided a proper temporal behavior is specified, and this behavior can be complex : the different harmonics follow different amplitude envelopes, which demands a lot of information. It is also possible to abstract more compact descriptions : for instance brass tones can be caracterized not by a fixed spectrum, but by a relation : the louder the tone, the richer the spectrum.

MUSICAL INFORMATICS PROVIDE SONIC REPRESENTATIONS WHICH ARE EXTENSIONS OF STRUCTURAL NOTATION

One should remember that musical notation, representing the music as a score, suggested the group of transformations of contrepoint - inversion and retrogradation. But sound itself must be represented in its temporal details. Computer synthesis allow various morphologies, including textures where separate entities such as notes may not be identifiable.

The spectrographic representation - frequency as a function of time, as in a musical score, but all harmonics are visible, with a darkness increasing with their amplitude - is probably the most suggestive. It is however biased and insufficient. For instance if two spectral lines are separated by an octave, their addition will be consonant and they will tend to fuse, whereas it will be very dissonant if the separation is one octave plus a semitone : this does not show clearly on a sound spectrogram. Evidently different forms of representation are needed. To provide a useful visual display, one has to take in consideration what one looks for.

For instance a logarithmic scale of frequency is better in certain cases - to show musical scales; but a linear scale will permit to recognize harmonics of a tone as equidistant lines. Incidentally these two cases correspond to the so-called wavelet and Gabor grain, represented on the following figure, and giving more rigorous mathematical treatments for running Fourier synthesis.

The integral representation is of course the waveform of the the sound, digitized as samples in the computer. As we have seen, it is not really meaningful. But it is certainly useful in certain cases. For instance, in mixing programs such as ProTools, one can look at the waveform at different scales, which is useful to cut portions of sound. It is worth mentioning that in such programs, sound files can be displaced along time, inserted and mixed : one can see "composition" at work in the litteral sense of the word, namely laying sounds together.

The synthesis method is a functional representation that is much more condensed and that lends itself to specific transformations. FM synthesis gives very compact representations on which one can efficiently perform strong global changes. To go to extreme detail, a representation of the same tone as the result of additive synthesis will work better. Hence one should use the possibility to represent the same sound as produced by different types of synthesis. One can indeed use such complete structural representations to produce musical variants : it can provide a help to composition in a much more general way than ordinary notation. Here the kind of representation used will emphasize this or that aspect of the sound and favor specific kinds of transformations.

Let me give a few instances of new possibilities that could not have been introduced without sound synthesis.

With synthesis, one can for instance compose sounds like chords. In the beginning of my work *Mutation*s (1969), the initial motive is first presented as a melody, then as harmony (a vertical chord), then as timbre : the gong-like tone sounds like the prolongation - the shadow - of the previous harmony.

Sounds can be changed intimately, while retaining the same harmonic substance : in my piece *Inharmonique*, for soprano and computer-synthesized sound, bell-like tones, composed like chords, are later turned into fluid textures.

In *Sabelith* (1966-1971) by John Chowning, fast pebble-like percussions with no definite pitch gradually turn into brassy tones (one would now use the term *morphing*). This is achieved by interpolating the frequency modulation synthesis parameters between those of the initial and the final tones.

Thus, instead of having discrete timbres, one can navigate amidst a continuum of timbre, and create the illusion of projecting the sound sources into space. The following figure gives an idea of how timbral interpolation can be achieved from additive synthesis models, as shown on this figure by John Grey.

By controlling fine aspects of the sound, the user can cause various figures to stand out from an indistinct background. In *Phone* (1981), Chowning takes advantage of the fact he discovered that micromodulations applied syntchronously to a group of components help the ear fuse these components as a single entity. By controlling such modulation, he makes voice-like tones to emerge from an indistinct magma of sound. This effect takes advantage of the fine control afforded by the computer, but also of the idiosyncrasies of perception. John Chowning has given a strong example of local and global formalization with recursive nested structures in his piece Stria (1977), which does take advantage of the specifics of hearing[4]. The piece unfolds beautiful sonorities with have transparency and consonance despite their richness, thanks to the calculation of proportions that determine both the internal harmony of the tones and the frequency relations between them. The macrostructure - the overall form - is also linked to the microstructure.

Thus, with synthesis, timbre and space can become part of the structural dimensions of music. Timbre is highly multidimensional, so it does not lend itself immediately to be arranged along scales unless one addresses some specific aspect. Certain composers argue that timbre cannot be the support of an elaborate discourse. To that, Max Mathews replies by giving an example of an elaborate communication system that is articulated mainly on timbre modulations, namely human speech!

---

[4] Before founding CCRMA - Center for Computer Research in Music and Acoustics - around 1974, John Chowning started his computer music research in the Stanford Artificial Intelligence Laboratory, directed by John McCarthy : his first sound synthesis program, Music 10 (for the PDP 10) was written in SAIL, a local variant of Algol. Although Chowning's work did not directly relate to AI, he implemented structures calling for advanced programming concepts.

DIGITAL SOUND PROCESSING : MERGING ELECTRONIC MUSIC AND MUSIQUE CONCRETE

Sonic structures of any origin can be modified and shaped in various ways. Advanced signal processing techniques - analysis-synthesis, filtering - allow to perform intimate transformations on existing sounds of any origin - for instance stretching time in a recording without changing the frequencies. This can help combine the sonic richness and variety of musique concrète and the strict control of parameters afforded by electronic music. Cross synthesis allows to imprint a given harmonic content on a natural sound - such as the sea - without definite pitch. Also a synthetic sound can be animated by the energy flux of a natural source like the sea or the wind.

The scenario of my work *Sud* is the gradual hybridation of natural sounds without definite pitch and of synthetic sounds with a specific pitch scale - on the trail of Cézanne, who wanted to marry "feminine curves and shoulders of hills".

PHYSICAL MODELLING : CREATING VIRTUAL WORLDS

If one accepts that perception has developed so as to extract from the sensory useful information about the environment, then it makes sense to resort to physical modelling. This approach can be considered as the complementary of artificial intelligence. AI aims at programming a mimicry of the subject's intellectual, perceptual and motor capacities. Physical modelling can be performed in the different sensory modalities - vision, touch, haptic perception and action : such modelling can replace not the subject, but the surrounding world, as observed by the subject through the windows of the various senses.

Our auditory capacities perform very well in the apprehension of mechanical causalities : thus we can hope that physical modelling provides the user with very effective handles for controlling salient aspects of the synthesized virtual objects, since it permits to directly control mechanical causalities to which perceptual systems are well tuned up. Indeed, signals obtained by physical modelling make strong sense to our hear, which is normal since we are equipped by evolution to deal with a mechanical world.

The approach of physical modelling is not to simply mimick the sensory signals, but to simulate the mechanical processes that produce them. It provides perceptually strong results, as witnessed by the work of ACROE, a French group from Grenoble that has been working for 25 years on this approach to develop new possibilites for research and art. ACROE has used a "particular" approach, based on the simulation of material particles that can be linked and bound in certain ways. Now the user can litteraly construct his or her own vibrating solid by assembling elementary modules simulating masses or springs.

Physical modelling is by nature multisensory, multimodal : a vibrating object can be seen and touched as well as heard. It allows to perform simulations, experiments, benchmarks. For instance Annie Luciani has used a model which assembles particles : by varying the interaction between particles, one obtains differend kinds of collective behavior.

Modelling of physical structure is an interesting appraoch to image animation. One can experiment with "virtual" morphogenesis. The challenge for the artist is not merely to create an illusion of our world, which is the usual goal of virtual reality, but rather to create appealing new virtual worlds.

Resorting to a hierarchical, multi-level approach, Cadoz (2002) has devised a physically-based formalism to control a complete musical piece, from its microstructure to its complete macrostructure. Here physical modelling is more than a metaphor, does not merely produce sound objects, its determines the evolution of a musical form.

Let us now go back to less sonic and more grammatical aspects.

LINGUISTIC ASPECTS

In music, perception happens along time. Listening to music involves expectancies about sonic relations and structures : these expectancies are either confirmed or deceived. Just as in a language, a musical style often implies a grammar that can be learned. Pitch scales are learned and they constitute pitch categories, grids: this phenomenon is similar to the learning of a language, which later imposes its specific phoneme distinctions when dealing with different languages.

The concern about renovating the grammar of music was also influenced by certain scientific developments, specially in information theory, linguistics and computer science. Music is different from language : it does not convey a message that could be translated into another musical dialect. Yet it clearly has certain linguistic aspects. It is irritating to hear certain physicists unaware of the tonal syntax claim that it does not make sense to differentiate between a B and a C flat in an equally-tempered tuning. In fact the same pair of sounds can imply different resolutions depending on the way you name them (that is, of the implied context).

For instance fa-si and fa-do bemol (F-B/ F-C flat)- imply different resolutions, namely mi-do in do major and sol bemol-si bemol in sol bemol major (E-C in C major, G flat-B flat in G flat).Since the work of Schenker in the early XXth century - prior to Chomsky), generative grammars for music have been developped : they imply the hierarchy of different levels, like in this diagram of a musical analysis by Lehrdal and Jackendoff.

CONCLUSION : ART, SCIENCE, TECHNOLOGY

Science is strongly affecting our representation of the world. Art offers other kinds of representations. Encounters are difficult, but mutual inspiration has long existed. From Pythagoras to contemporary musical acoustics and scene analysis, the inspiration often came from music. The British historian Geoffroy Hindley believes that the idea of cartesian coordinates originated in the western world because it was inspired by the western notation.

Art calls for technology. An emergent technology can produce leaps into both science and art. There are many examples in the past. But art is not only a result, it is also a ferment. Musical desires have inspired and shaped the developement of digital sound technology. Today the digital domain deals with intellectual as well as with material structures, it can both generate the vocabulary and impose the syntax for art works. This has already brought considerable changes in the processes, even though some argue that these changes have only rarely brought radically new forms of art. One may reply that we have difficulty sensing the radical novelty of certain proposals. For instance the beautiful piece *Stria* by John Chowning is very new in its relation between microstructure and macrostructure, but this novelty is not necessarily striking - just as Debussy introduced peaceful revolutions in musical form.

Perhaps we are at the beginning of a geological revolution, with effects that are in the end overwhelming, but extremely slow to change the landscape (or the soundscape). Hence one must work on the necessary exploration of novel territories and take into consideration the fact that art is meant to be appreciated through our senses, music is meant to be heard : hence the importance of understanding musical perception, which bridges objective structures and esthetic experience. Building a body of knowledge and knowhow requires a cooperative effort : the artistic project may continue to be individual, but all members of the community can contribute to the exploration through a new mode of research which is both scientific, technological and artistitic, without frontiers, hierarchies or subordinations. Such transdisciplinary research has already emerged, and the growth of networking promises to help develop it through some kind of collective craft and intelligence.

REFERENCES

A.S. Bregman. Auditory scene analysis - the perceptual organization of sound. Cambridge, Mass: M.I.T. Press, 1990.

C. Cadoz (2002). The physical model as a metaphor for musical creation : pco..TERA", a piece entirely generated by a physical model. Journées d'Informatique Musicale, Marseille.

M. Chemillier & F. Pachet, coordinateurs (1998). Recherches et applications en informatique musicale. Hermès, Paris.

J.Chowning. The simulation of moving sound sources. Journal of the Audio Engineering Society, 1971, 19, 2-6.

J. Chowning. The synthesis of complex audio spectra by means of frequency modulation. Journal of the Audio Engineering Society, 1973, 21, 526-534.

J. Chowning,. Computer synthesis of the singing voice. In Sound generation in winds, strings, computers, Stockholm, Sweden: Royal Swedish Academy of Music, 1980, 4-13.

Chowning, J. Frequency Modulation Synthesis of the singing voice. In M.V. Mathews, ., & J.R. Pierce, J.R., ed. Current Directions in Computer Music Research, 1989, 57-63.
J. Chowning,, & D. Bristow. FM theory and applications: by musicians for musicians. Tokyo: Yamaha Foundation, 1987.
D. Deutsch (1982). Grouping mechanisms in music. In D. Deutsch, ed., The psychology of music, Academic Press, 99-134.
C. Dodge & T. A. Jerse (1997, second edition). Computer music - synthesis, composition, and performance. Schirmer, New York.
J.J. Gibson (1966). The senses considered as perceptual systems. Houghton Mifflin, Boston.
F. Lerdahl & R. Jackendoff (1983). A generative theory of tonal music. M.I.T. Press, Cambridge, Mass.
T. Licata, ed. (2002). Electroacoustic music : analytical perspectives. Greenwood Press, Wesport, CT.
M.V. Mathews (1969). The technology of computer music. M.I.T. Press, Cambridge, Mass.
M.V. Mathews & J.R. Pierce (1989). Current directions in computer music research. M.I.T. Press, Cambridge, Mass. (avec un disque compact d'exemples sonores).
J.R. Pierce (1983). The science of musical sound (with a compact disc of sound examples). Scientific American Library.
J.C. Risset, 1985, Computer Music Experiments 1964- ... . Computer Music Journal 9 n° 1, pp. 11-18 (avec 5 mn d'exemples sonores sur disque). Réédité in C. Roads, editor, The Music Machine, 1989, M.I.T. Press, Cambridge, Mass.
J.C. Risset, 1986, Pitch and rhythm paradoxes: Comments on "Auditory paradox based on a fractal waveform", Journal of the Acoustic Society of America, 80, pp. 961-962.
J.C. Risset,1992. Composing sounds with computers. In J. Paynter, T. Howell, R. Orton & P. Seymour, editors, Companion to Contemporary Musical Thought, volume I, Routledge, London, 583-621.
J.C. Risset (1999). Composing in real-time? (avec 8 mn d'exemples sonores sur disque compact joint à la revue). In "The Aesthetics of Live Electronic Music", Contemporary Music Review 18, Part 3, 31-39.
J.C Risset (2001). Portraits polychromes. INA-GRM and CDMC, Paris.
J.C Risset (2001). (biographie, catalogue, écrits, recherches, musiques avec électronique, discographie): website developped by Laurent Pottier, http://www.olats.org (Rubrique "pionniers et précurseurs")
P. Schaeffer (1966). Traité des objets musicaux. Editions du Seuil, Paris.
R.N. Shepard (1964). Circularity of relative pitch. Journ. of the Acoust. Soc. of America, 36, 2346-2353.
R.N. Shepard (1981). Psychophysical Complementarity. In M. Kubovy & J.R. Pomerantz, editors, Perceptual Organization, Erlbaum, Hillsdale, N.J., 279-341.
J. Sundberg & B. Lindblom (1976). Generative theories in language and music description. Cognition 4, 99-122.
H. Vaggione (1996). Articulating microtime. Computer Music Journal 20 n° 2, 33-38..
H. Vaggione (2001). Some ontological remarks about music composition processing. Computer Music Journal 25 n° 1, 54-61..
E. Varèse (1917). In 391, New York. Quoted in E. Varèse, Ecrits, collected by Louise Harbour, Christian Bourgois, Paris 1983.