



Joan Riera Robusté

**Audição Espacial e Percepção do Som na
Composição Musical**

**Spatial Hearing and Sound Perception in Musical
Composition**



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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Música, realizada sob a orientação científica do Doutor João Pedro Paiva de Oliveira, Professor Titular da Universidade Federal de Minas Gerais.

*To Josep, Maria Dolors,
Jordi, Marta, Toni, Bernat,
Antonie, and Mimi*

o júri

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palavras-chave

Composição musical, música electrónica, espacialização do som, audição espacial, percepção do som.

resumo

Esta tese explora as possibilidades da Audição Espacial em relação à percepção do som e apresenta três composições acusmáticas baseadas numa estética musical que enfatiza esta relação e a incorpora como uma parte do seu discurso musical. A primeira característica importante destas composições é a utilização exclusiva de sinusóides e de outros sinais sonoros invariáveis no tempo. Embora estes tipos de sinais não apresentem variações no tempo, é possível percepcionar variações de altura, intensidade e timbre assim que estes se movem no espaço, devido aos processos acústicos envolvidos na audição espacial. Para enfatizar a percepção destas variações, esta tese propõe dividir um som em múltiplas unidades e espalhá-las no espaço utilizando vários monitores dispostos à volta da plateia. Além da percepção de variações de características do som, também é possível criar variações de ritmo e de textura que dependem de como os sons são dispostos no espaço. Esta estratégia permite superar o problema de “sound surrogacy” implícito na música acusmática, uma vez que é possível estabelecer relações causa-efeito entre o movimento do som e a percepção de variações de características do som, variações do ritmo e textura. Outra consequência importante da utilização da fragmentação com a espacialização do som é a possibilidade de criar campos sonoros difusos, independentemente dos níveis de reverberação da sala, e de criar espaços sonoros com uma certa profundidade, sem utilizar nenhum tipo de *delay* ou reverberação artificiais.

keywords

Musical composition, electronic music, sound spatialization, spatial hearing, sound perception.

abstract

This thesis explores the possibilities of spatial hearing in relation to sound perception, and presents three acousmatic compositions based on a musical aesthetic that emphasizes this relation in musical discourse. The first important characteristic of these compositions is the exclusive use of sine waves and other time invariant sound signals. Even though these types of sound signals present no variations in time, it is possible to perceive pitch, loudness, and tone color variations as soon as they move in space due to acoustic processes involved in spatial hearing. To emphasize the perception of such variations, this thesis proposes to divide a tone in multiple sound units and spread them in space using several loudspeakers arranged around the listener. In addition to the perception of sound attribute variations, it is also possible to create rhythm and texture variations that depend on how sound units are arranged in space. This strategy permits to overcome the so called "sound surrogacy" implicit in acousmatic music, as it is possible to establish cause-effect relations between sound movement and the perception of sound attribute, rhythm, and texture variations. Another important consequence of using sound fragmentation together with sound spatialization is the possibility to produce diffuse sound fields independently from the levels of reverberation of the room, and to create sound spaces with a certain spatial depth without using any kind of artificial sound delay or reverberation.

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INTRODUCTION

*“Alles fundament ehrt man, darf aber nicht aufgeben,
irgendwo wieder einmal von vorn zu gründen.”¹*

Johann Wolfgang Goethe

Nowadays, considering sound spatialization as a formal element of musical composition is not only common but, in many aspects, necessary. Since the second half of the twentieth century it has been widely used and has a tremendous importance in the development of new compositional methods and techniques. In addition to frequency, amplitude, timbre and duration, sound spatialization is incorporated as a fifth parameter with the ultimate aim of achieving dynamism and musical clarity, as it permits the movement of sounds through sound trajectories to create spatial shapes and achieve sound directionality; the differentiation of spectral components, timbres, rhythms, velocities, textures, layers or sections of a piece to achieve musical clarity and transparency (which in turn permits a dialog between them); the spatial fragmentation of melodies, harmonies, gestures; and the separation of simultaneous musical events so they can be perceived in isolation from one another and in different orders.

Indeed, the early functions of space employed in the antiphonal music of the Renaissance were assimilated and expanded in the twentieth century by composers as Russolo, Milhaud, Ives, Schaeffer, Boulez, Stockhausen, Xenakis, and Nunes among many others. Of all of them, Stockhausen seems to have used space in more diverse ways in both instrumental and electroacoustic music. Gisela Nauck's *Musik in Raum – Raum in der Musik* (Music in Space – Space in Music) summarizes the spatial techniques and strategies used by Stockhausen:

- 1) spatialization as a function and consequence of serial techniques,
- 2) the creation of new, physically experienceable sound spaces that are relatively independent of the architectonic space of the performance,

¹ “We should honor all fundamentals, but we shouldn't give up, somewhere anytime to start from the beginning” (translated by the author).

- 3) new communicative and receptive situations through spatial music, and
- 4) the dialectic of musical forms and experienced acoustic space as outer and inner spaces.²

All these functions of real space are described in detail in chapter 1, and are used, as we will see, by a large number of composers and compositions.

In relation to point two, the possibility to create new, physically experienceable sound spaces increased substantially since the mid-seventies thanks to Ambisonics and Wavefield Synthesis (WFS), which attempt to improve the perception of reconstructed sound fields offered by other techniques such as stereophonic, quadraphonic or surround-sound systems. In contrast to surround sound systems,³ which are frontally oriented, quadraphonic sound was one of the earliest attempts to develop standardized sound systems for the presentation of spatialized audio by using four loudspeakers situated equidistantly at the four corners of the listening space. The main problem with quadraphonic systems is the phantom images they create, even for a single listener situated at the center. With Ambisonics the problem of perceiving phantom images persists, as it is only efficient for a listener situated at the center of the loudspeaker arrays. However, the encoded signals can be used in a wide variety of loudspeaker arrays, from mono to stereo, horizontal arrangement of loudspeakers or even periphonic (at different heights) arrays.⁴

WFS, which is used in this thesis, is a type of holophonic reproduction process that enables, by analogy with visual holograms, to capture or synthesize a sound scene while conserving the spatial characteristics of distance and direction. It permits the potential reproduction of the position of sounds over an extended listening area, which, in contrast to Ambisonics – which is oriented to a single listener – is very convenient in the presentation of spatial music. In addition, WFS can situate point sources behind and in front the loudspeaker arrays.⁵ This system was first initiated by Berkout at the University of Delft

² Nauck, Gisela, 1997, *Musik im Raum - Raum im Musik: Ein Beitrag zur Geschichte der Seriellen Musik*, Franz Steiner Verlag, Stuttgart, p. 23 (translated by the author).

³ Surround systems (5.1) are commonly used in cinemas as well as for the reproduction of music and films presented in DVDs (Digital Versatil Disk). This system consist in five loudspeakers, three situated at the front (center, left and right), and two at the sides (one surround left and one surround right). One additional loudspeaker is used for the low frequencies as sub-bass effects and is also at the front. This technique is primarily intended to support a frontal visual image while maintaining backward compatibility with traditional two-channel stereo, as the front left and right loudspeakers maintain an angular separation of +/- 60° (Gerzon, M. A., 1974, *Surround Sound Psychoacoustics*, Wireless World, Vol. 80, pp. 483-486).

⁴ Bamford, J. S., 1995, *An Analysis of Ambisonic Sound Systems of First and Second Order*, Doctoral Thesis, University of Waterloo, Canada.

⁵ Franco, A. F., Merchel, S., Pesqueux, L., Rouaud, M. and Soerensen, M. O., 2004, *Sound Reproduction by*

around 1980, being later developed by other important research centers such as IRCAM in Paris, The Institute for Music and Acoustics at ZKM in Karlsruhe, and the Technische Universität Berlin, where I partially worked on the conception of the compositions included in part two of this thesis.

After studying the diverse functions of space in music composition, one realizes that even though sound spatialization has an important role in the inner and outer form of the pieces, it is normally used either to reflect on or emphasize certain aspects that exist already in the composition, or to solve problems that appeared with new musical aesthetics (i.e. to achieve musical clarity when using polytempi, polytonalities and the collage of different recorded sounds, or to solve the problem of musical motionlessness that appeared with the serial or stochastic organization of notes). Moreover, formal elements such as melodies, rhythms, sound objects, gestures, textures, timbres, etc. are usually designed a priori, and sound spatialization and sound movement are used either to provide transparency to the musical discourse or to achieve certain dynamism by molding a specific shape and directionality to sound.

However, sound spatialization together with the new possibilities of electroacoustic sound production and diffusion offer the opportunity to approach musical composition from a “new beginning”⁶, to use Stockhausen's expression when he discovered the potentials of serial organization of sound parameters to redefine the basis of his musical language. My aim is to use sound spatialization as part of the formal structure of sound itself, instead of using it as part of the formal structure of music. This implies that sound spatialization and sound movement alter the perception of the sound attributes on the one hand, and create the musical events themselves on the other. To explore the possibilities of sound spatialization in relation to the perception of sound, I was forced to find new strategies and techniques that fostered this relation and to incorporate it as part of a musical discourse. To reach this goal, it was necessary to investigate

Wave Field Synthesis, Project Report, Aalborg University.

⁶ The expression *Neuanfang* (new beginning) was used by Stockhausen to point out the importance of the new aesthetic possibilities that Messiaen's *Mode de Valeurs et Intensités* were offering, which are in the origin of the serial organization of the musical parameters. (cf. Kurtz, Michael, 1988, *Stockhausen. Eine Biographie*). Similar to serialism, which introduces a new way of organizing frequency, amplitude, duration, timbre, the expression “new beginning” refers here to the necessity to find new aesthetic approaches that permit to incorporate sound spatialization to modify the perception of loudness, pitch and tone color variations and to emphasize these variations to incorporate them as part of a musical discourse.

- 1) to what extent sound localization can be used to perceive sound attribute variations, namely that parameters such as pitch, loudness, and tone color become functions of the position and movement of sounds in space,
- 2) how sound can be organized in time and space so that such sound attribute variations are emphasized and better perceived, and
- 3) if such sound attribute variations are important enough to be incorporated into a musical discourse.

In relation to point one, the first experiments undertaken in this thesis show empirically that a 408 Hz sine wave radiated successively through eight loudspeakers situated around the listener⁷ is perceived with pitch, loudness and tone color variations. This acoustic phenomenon is extensively investigated in the field of spatial hearing by researchers as Blauert, von Békésy, Shaw, Ternishi, Bregman, and many others. Jens Blauert's *Spatial Hearing: The Psychophysics of Human Sound Localization*⁸, for instance, presents extensive research on the influence of the external ear on spatial hearing, establishing that during their path to the ear drum, sounds undergo linear distortions (i.e. pressure level, phase, and group delay variations) that depend on the direction and distance of the sound sources, which permit the auditory system to localize sounds in space. These linear distortions are usually perceived as pitch, loudness and tone color variations.

However, the experiments presented in this work show that when using pure tones the perception of such sound attribute variations is very subtle. Therefore, it is deduced that such variations would be highly masked when using more complex sounds, i.e. sounds whose spectra contain frequency, amplitude, and timbre variations in time. This assumption is also pointed out by Rossing (1989), who states that the effect of sound intensity on pitch perception is especially relevant when using sine waves. For this reason both experiments and compositions presented in this thesis use sound signals whose energy or power spectra are constant over time, such as sine waves, square waves, and triangle waves. As it is demonstrated through the compositions presented in part two of this research, using such types of sound signals makes it possible to perceive enough sound attribute variations that they can be incorporated as part of the musical discourse.

⁷ See test 1.1 in the appendix.

⁸ Blauert, Jens, 1997, *Spatial Hearing: The Psychophysics of Human Sound Localization* (revised edition),

Sound-Space Strategy

In order to emphasize the perception of sound attribute variations related to sound localization, this thesis proposes the following formal organization of tones.⁹

First, each sustained tone is not continuous but constituted by the sum of successive small sound units called notes.¹⁰ The units or notes that constitute the same sustained tone have the exact same frequency and duration to avoid the perception of melodic contours and rhythms, so the attention can focus exclusively on the perception of sound attribute variations produced by varying the position of notes in space (see figure 39, p. 103).

Second, these notes are organized in groups of eight units,¹¹ referred to as “8-note groups”, which are radiated through eight loudspeakers arranged around the listener in the approximate shape of a regular octagon (see figure 19, p. 69). The use of eight loudspeakers offers the possibility to perceive the notes in the 8-note groups from eight different angles of incidence to the ears, which prove to be enough for the purposes of this thesis.¹²

Third, four parameters are used to organize the temporal and spatial form of sound, which are the “relative” and “absolute” distances and the “relative” and “absolute” positions. The relative distance defines the temporal distance between the notes in the 8-note groups, while the absolute distance refers to the distance between the 8-note groups themselves. As explained in chapter 4, these parameters are very important in the creation

Cambridge: MIT Press.

⁹ We consider tones as “sounds with a definite pitch and duration, as distinct from noise and from less definite phenomena (...)” (Harvard Dictionary of Music, 1970, Second Edition, The Belknap Press of Harvard University Press, Cambridge, Massachusetts, p. 856).

¹⁰ Even though it would be more appropriate to call them 8-*tone* groups, we use the term notes and not tones to differentiate them from the “sustained tones” mentioned later. Notes are defined as tones with very short durations, and, similarly to its most common meaning, “(...) they represent the pitch and duration of a sound (...)” (*The New Harvard Dictionary of Music*, 1986, The Belknap Press of Harvard University Press, Cambridge, Massachusetts, p. 548), which differentiates the 8-note groups one another.

¹¹ The number of loudspeakers determines the number of notes in each note group, as each note can occupy eight different spatial positions.

¹² Many composers use eight loudspeakers in their compositions, such as Stockhausen and Traux, because it guarantees an optimal sound spatialization. Even Stockhausen, who fought for the construction of specific concert halls for the diffusion of spatialized music (e.g. the pavilion in Osaka), moved gradually toward more simplified solutions such as Quadraphonic sound and Ambisonics. He was one of the first composers to adopt an arrangement of eight loudspeakers in his composition *Sirius* (1975-77), which was used extensively

of diverse sound materials.

The relative position defines the spatial position of the notes inside the 8-note groups using all eight loudspeakers or spatial positions before one of them is repeated. The relative position of the notes in 8-note groups in both the experiments and compositions is organized using eight fixed relative position rows, or “Original” (O) position rows (see figure 40, p. 105) of the notes in the 8-note groups. Assigning different relative positions to the 8-note groups permits the perception of pitch, loudness, and tone color variations. The absolute position reorganizes the position of the notes dictated by the relative position using less than eight loudspeakers, as shown in figures 57 and 58 (pp.125-126). The absolute position organizes the 8-note groups in space using different sound-space densities.¹³

One important consequence of using such temporal and spatial parameters is that the 8-note groups are perceived with rhythm and texture variations, in addition to the sound attribute variations, as the absolute position varies the amount of real space between the notes in 8-note groups, i.e. the sound-space density. For instance, when the eight notes in the 8-note groups are emitted by one loudspeaker, there is no “real” space between the notes in the 8-note groups, so the sound-space density is the highest possible. On the contrary, when all eight loudspeakers are used, the resulting sound-space density is the minimum possible, as the maximum extension of space between the notes one another is used to radiate the same amount of notes. The amount of loudspeakers implies more or less “physical” (or real) space inside the 8-note groups, so they are more or less dense. Sound-space density has, as it is demonstrated through this research, important consequences in relation to sound perception.

To investigate the effects of sound spatialization on sound perception, this thesis presents different types of sound materials, all of them using 8-note groups with different sound signals, frequencies, note durations, and relative and absolute distances. Depending on the number of successive 8-note groups, sound materials are organized in two

for the rest of his career.

¹³ The term “sound-space density” represents the relation between sounds and real or physical space. Density defines the “quantity of things in a given area or space” or “mass per unit volume” (*The Oxford Dictionary, Thesaurus, and Wordpower Guide*, 2001, Oxford University Press, New York, p. 324). If we metaphorically consider sound as a compact substance, the 8-note groups represent a fixed number of sound units (mass) that occupy more or less “real” space (volume) depending on how many loudspeakers radiate them.

categories: gestural and textural. The gestural sound materials include attacks, gestures, and sound objects, while the textural ones include sustained tones, continuums and textures. These sound materials are played through different relative and absolute positions to evaluate the consequences that sound localization and sound-space density variations have on the perception of sound attribute, rhythm and texture variations.

In addition to the perception of sound attribute, rhythm and texture variations, sound-space density is also very important to mold the spatial shape and directionality of the 8-note groups as well as to achieve sound clarity and transparency in polyphonic musical situations. However, the most important consequence of using this type of temporal and spatial organization of the 8-note groups is the perception of cause-effect relations between sound spatialization and the perception of sound attribute, rhythm and texture variations. This dialog is the main characteristic of the compositions presented in the second part of this thesis.

Formal Organization of the Thesis

The thesis is divided into three parts: part 1, theoretical research; part 2, practical application; and the appendix, which presents the experiments. Part 1 comprises five chapters, which include:

1) explanation of the functions of real¹⁴ space,

¹⁴ The term “real” refers here to the physical dimension of space, and it is used to differentiate it from other metaphorical spaces. Gisella Nauck (Nauck, 1997, pp. 22-29) resums all possible spaces related to sound and music as:

- the sonic space (Schall Raum), as medium for the propagation of the sound waves in space and time,
- the architectonic space (architektonische Raum), as the specific space of the performance, the inside space of any kind of building,
- the musical space (musicalische Raum), as the sound consequences formed through the acoustic characteristics of the space, which occurs basically during the performance of a musical work in a architectonic space,
- the sound location (Tonort), which in general sense refers to the specific location of a sound source (instrument, loudspeaker, sound and all type of noise) in a closed and also open space,
- the sound space (Klangraum), which represents the “acoustic checkout” of the geometric spaces via the composition, whenever the musical form/structure/Gestalt is spatialized
- the intended space (intendierte Raum), as idea in the imagination of the composer,
- the composed space (komponierte Raum), or notational space, as the relation of the musical elements as realized in music paper,
- the tone space (Tonaum), as the vertical structure of sound.

- 2) theoretical research on the processes of spatial hearing that influence the perception of sound attribute variations,
- 3) description of the temporal and spatial organization of sounds proposed in this thesis,
- 4) description of the elaboration of sound materials used in the compositions,
- 5) analysis and evaluation of the compositions presented in part 2, where all the previous functions of space as well as temporal and spatial formal organizations are applied.

Part 2 presents the practical application of the results of the research undertaken in part 1, and consists of three acousmatic compositions: *Topos* (2011), *Polyphonic Continuum* (2012), and *Musical Situation I* (2012). These compositions are presented in DVD 3, containing Pro Tools¹⁵ sessions with the octophonic versions of the pieces.

The appendix contains the experiments realized in this thesis, which include a description of the objectives, a detailed description of all parameters involved in the elaboration of the sound material, and an evaluation of the sound material in relation to the perception of both sound localization and the perception of sound attribute, rhythm and texture variations produced by sound localization and sound-space density variations. It presents as well two DVDs containing Pro Tools sessions with the audio files corresponding to each test.

Chapter 1 presents an overview of the functions of real space used in the compositions presented in part 2 of this thesis, an historical overview, and as well as examples of works by composers such as Giovanni Gabrieli, Ives, Boulez, Stockhausen, Xenakis, Nunes, and many others. It frequently refers to the use of sound spatialization in books such as Bryant's *The 'cori spezzati' of St Mark's: myth and reality*, as well as in articles and essays written by the composers such as Boulez and Stockhausen, or by other authors as G. Knack, H. Kitchener, J. Cot, or H. Sable.

First, space can be used as part of the formal structure of the compositions, either to

To explore the functions of the real space in musical composition it is necessary to consider the architectonic space, musical space, sound location, intended space, and sound space. Even though the intended space and sound spaces refer to mental and metaphorical spaces, they are here also considered as they are ultimately projected in the real space determining and influencing the position and movement of sounds.

¹⁵ Pro Tools is a digital audio workstation used for musical recording and editing.

emphasize the inner form of a composition as in the *cori spezzati* used by Giovanni Gabrieli in *In Ecclesiis*, or as a parameter on an equal plane with pitch, duration (rhythm), amplitude, and timbre, as in Boulez's *Répons* or Stockhausen's *Kontakte*.

The second function of space is to achieve more clarity and transparency in complex polyphonic situations, as in the music of Charles Ives, Russolo, or Milhaud. Ives's piece *The Unanswered Question*, for instance, presents three differentiated layers where the use of different tempi, tonalities, timbres, rhythms and amplitudes together with the spatialization of each instrumental group permits one to differentiate each layer from the others. In Stockhausen's *Gruppen für drei Orchester* or Nunes' *Quodlibet*, spatial separation is more important and necessary to distinguish each layer, as the simultaneous layers – in contrast to Ives – do not use contrasting tonalities, dynamics, rhythms, or timbres. Natasha Barrett uses multiple loudspeaker arrays to differentiate the frequency components of pure electronic sounds, showing that sound movement permits the distinction of more frequency components than static sound sources. This strategy is reminiscent of the sound trajectories used by P. Schaeffer to achieve musical relief.

The third function of space is to resolve two problems that appeared with serial music: musical immobility and the impossibility of achieving sonic continuity. These stationary situations occur when it is possible to perceive neither a directional time flow nor musical continuity due to constant successive changes in sound parameters. These issues are discussed by Stockhausen in his essays *Elektronische und Instrumentale Musik* and *Musik in Raum* (1958), where he suggests that sound spatialization and sound movement can be used to articulate longer time phrases and to clarify the complex relations between layers. This explanation is accompanied by examples of Stockhausen's piece *Kontakte*, where he uses several types of sound movement at different speeds and sound location variations to articulate the temporal durations of musical events.

The fourth function of space is to open the musical discourse to multiple perspectives by permitting the listener to build his or her own musical discourse. This indeterminacy is found, for instance, in Stockhausen's *Ensemble*, *Musik für ein Haus* or *Musik für die Beethovenhalle*, which present simultaneous pieces performed in different spaces. The listener can move freely through the rooms, thus deciding the order and duration of the pieces and establishing his own relations between events occurring at different spaces.

Space can be used as well to achieve a certain plasticity by molding sounds in

space. Stockhausen was one of the first composers to use the spatialization of instrumental groups with similar instrumentation to move sounds in space and mold them with a specific shape and directionality, as in *Gruppen für drei Orchester*. At the World's Fair at Osaka in 1970, recalling Schaeffer's *potentiomètre d'espace*, he created horizontal and vertical spatial trajectories projected manually through fifty-five loudspeakers arranged in seven rings situated above and below the audience. Xenakis likewise uses sound trajectories to create sonic images of circles, squares, or a surface projecting sounds through multiple loudspeakers, while Chowning uses Lissajous Figures¹⁶ to create sophisticated sound trajectories and sound figures using a Quadraphonic sound system.

Together with sound spatialization, some composers were also interested in the interaction between sound and architectonic or acoustic space, which, depending on the levels of reverberation, sound absorption and resonance, deforms the composed musical “gestalt” proposed by the composer, creating new temporal and spatial shapes. Two examples of this interaction are *Musik für die Beethovenhalle*, where Stockhausen takes into consideration the resonant behavior of architectonic spaces, which he defines as being not neutral and having a particular acoustic character, and Nunes' *Quodlibet*, which was written taking into consideration the enormous architectonic space of the Coliseu dos Recreios in Lisbon.

An important function of sound spatialization is the creation of sound spaces independent of architectonic space. This is achieved by spreading the instruments or loudspeakers in space and creating sound trajectories, echoes, and reflections, or by manipulating sounds using amplitude variations or artificial delays, echoes, spectral filters, etc. The perception of such composed sound spaces is always problematic, as the intention of the composer is not always well perceived due to the position of the listeners, or the sound reflection and sound absorption of architectonic or musical spaces. Xenakis tries to overcome this problematic by using the *polytop*, which adds a visual element to support the

¹⁶ The Lissajous figure (see figure 10, p. 53), also called Bowditch curve, “(is the curve) pattern produced by the intersection of two sinusoidal curves the axes of which are at right angles to each other. First studied by the American mathematician Nathaniel Bowditch in 1815, the curves were investigated independently by the French mathematician Jules-Antoine Lissajous in 1857-58 (...) (sinus) with identical amplitude and frequency but varying phase relation, ellipses are formed by varying angular positions (...) if the curves are out of phase and differing in frequency, intricate meshing figures are formed (...) In general the curves can be used to analyze the properties of any pair of simple harmonic motions that are at right angles to each other” (The New Encyclopedia Britannica, 2002 (15TH edition), Encyclopedia Britannica, Inc, USA, p. 393).

auditory spatial trajectory of sounds. As pointed out by D. Smalley,¹⁷ the imaginary space created by particular timbre or reverberation either by a stereo field recording or produced synthetically, can be drastically distorted when performed in large spaces, same as the perception of proximity or intimacy pretended by the composer.

Space is also used to alter the perception of sound attributes, as proposed in this research. One example is Stockhausen's *Cosmic Pulses*, which uses the rotation of sound around the audience at different speeds to produce variations on the perception of pitch and timbre, as well as on the perception of specific sound fields. Ives, for instance, uses different distances between the instruments to achieve musical perspective, which implies the perception of specific timbres and loudnesses associated with distance.

This is also true of soundscape music introduced by Murray Schafer, Barry Truax, and Hildegard Westerkamp. This type of music is based on field recordings, which implies that each sound has a specific sound space determined by the characteristics of the environment. The fact that the source of each sound is recognized permits one to interpret the sound attributes to create a mental image of its spatial distance. The music of Llorenç Barber (1948) and Henry Brant (1913-2008), for instance, extensively explores the dimensions of real space by using the entire extension of a city, through the bells of its multiple churches or arranging multiple instrumental groups through distant places of its urban geography, creating a dialectic between sound perception and spatial distance.

This thesis proposes the use of sound localization to produce the perception of pitch, loudness, and tone color variations, which occur together with the processes involved in spatial hearing. How the perception of such sound attributes is emphasized so they can be incorporated as part of a musical discourse is explained in detail in the course of this dissertation.

All the spatial strategies explained in this chapter are used in the compositions presented in part 2 of this thesis, as they contribute to the perception of sound attribute, rhythm and texture variations, sound clarity and transparency; spatial shapes and sound directionality; the diffusion of sound fields; or the creation of multiple perceptions of the same piece.

Chapter 2 presents a detailed description of the psychophysics of human sound

¹⁷ Smalley, D., 1997, *Spectromorphology: Explaining Sound-Shapes*, Organized Sound, Vol. 2(2), Cambridge University Press, pp. 107-126.

localization. Although the research on spatial hearing focuses on the spatial attributes of the auditory event, i.e. the influence of the external ear in relation to spatial hearing, it contains valuable information that explains why sound is perceived with sound attribute variations depending on its position in space.

To better understand the influence of the external ear on the perception of sound attribute variations, a distinction is made between free sound fields, i.e. those with no reflections, and non-free sound fields, i.e. sound fields where the obstacles create reflections and echoes. The experiments using free sound fields undertaken by Blauert, Batteau, Shaw, Teranishi and Metz among others, prove that the transfer functions $\underline{A}(f)$ that occur at the pinna, ear canal, ear drum and head imply pressure level, phase delay, and group delay variations that depend on the angle of incidence of sound signals at the external ears, which explains why sounds are perceived with sound attribute variations depending on their position in space.

From all the transfer functions that occur at the external ear, pressure level differences seems to be the most important for the perception of pitch, loudness and tone color variations. Studies on spatial hearing demonstrate that the external ear codes different sound pressure variations according to the direction and distance of the sound source. Blauert¹⁸ points out that these interaural sound pressure level variations at the ear drum are considered the most important information used by the auditory system to determine sound localization compared to group and phase delay variations. Indeed, the tests included in this thesis show that very similar loudness and tone color variations are also perceived by manipulating the amplitude levels of the same sound signal without varying its position.

In addition, similar effects on the perception of loudness and tone color can be achieved by varying the distance of the sound signals. This is the case at distances less than 15m. To explain why tone color becomes darker when the sound source is brought closer to the subject, von Békésy deduces that broadband signals need more perceptual weight (dB) in comparison with the high-frequency components. At greater distances, the influence of the air paths to the ears also has an important influence on the perception of timbre, as they attenuate higher frequencies more than low ones.

This chapter explains as well why sound localization influences the perception of pitch. When notes in the 8-note groups, the basis of our scientific and artistic research, are

¹⁸ Blauert, 1997, p. 56.

radiated from different sound locations, they are perceived with important pitch variations in addition to loudness and tone color variations, producing a microtonal melody. Studies undertaken by Rossing and Moore prove that these variations are also produced by sound pressure level variations, which in this case are a consequence of the position of sounds and the transfer functions occurring at the external ear.

The possibility to create diffuse sound fields independently of the levels of reverberation of the acoustic space is an important characteristic of using 8-note groups and multiple sound sources. Normally, diffuse sound fields occur when the levels of the primary sounds are masked due to the level of reverberation in the room. In this case, however, the successive 8-note groups radiated through multiple loudspeakers spread around the listener create an exceptional amount of correlated and uncorrelated sound signals between the primary sounds and early and late reflections, which may increase the level of the reverberation.

The influence of acoustic space is also relevant on the perception of 8-note groups with short note durations, as some notes in the 8-note groups are masked by the early reflections. This phenomenon is explained by the “echo threshold”, the “law of the first wave front”, and “summing localization”, which determine the delay time between the direct sound signals and the perception of the first echo, the masking of the early reflections and the influence of the early reflections on sound localization.

Chapter 3 explains how parameters such as relative and absolute distances, relative and absolute positions and sound-space densities are applied to the 8-note groups. On the one hand, these parameters permit the creation of different sound materials by using different sound signals, note durations, and frequencies as well as relative and absolute distances, as described in chapter 4. On the other hand, the spatial arrangement of notes in the 8-note groups following different relative and absolute positions and sound-space densities permits the perception of sound attribute, rhythm, and texture variations.

The spatial organization of the 8-note groups is done following two steps. First, each note in the 8-note groups is assigned a position in space, which is determined by the position of eight loudspeakers situated around the listener. This position is referred as relative position, and implies the use of all eight loudspeakers. Secondly, the relative position is then used to reorganize the 8-note groups using less than eight loudspeakers, which is referred as absolute position. The number of loudspeakers implies more or less

spatial distance between the notes in the 8-note groups, which is here referred to as sound-space density (see figure 13, p. 58).

Chapter 3 also explains the results obtained in the main research goal of this thesis, which is the perception of cause-effect relations between the sound movement through different sound locations and sound-space densities, and the perception of sound attribute, rhythm, and texture variations. Indeed, an important characteristic of the musical discourse of the compositions presented in part 2 of this thesis, is the possibility to perceive a dialog between sound and space.

Chapter 4 summarizes the process of creating multiple diverse sound materials realized in the numerous tests included in the appendix, and evaluates them according to the perception of sound attribute, rhythm, and texture variations that occur as functions of sound localization and sound-space density variations. Each type of sound material uses individual or multiple successive 8-note groups with different sound signals, frequencies, note durations, and relative and absolute distances, and can be divided in two types, gestural and textural. Gestural sound materials use either individual 5-note groups (attacks), a limited number of repeated 5-note groups (gestures), or short portions of textures (sound objects). The textural sound material is defined by using long sequences of 8-note groups, which are classified as sustained tones, continuums and textures depending on the amount of temporal and spatial variations.

Only the sound material that proved to be more efficient in relation to the perception of sound attribute, rhythm, and texture variations is later used as sound material for the compositions presented in part 2.

Chapter 5 explains three acousmatic compositions, *Topos*, *Polyphonic Continuum*, and *Musical Situation 1*, which represent the practical part of this thesis (part 2), and evaluates the importance of the perception of sound attribute, rhythm, and texture variations in relation to the type of sound material, sound space, and formal structures used. *Topos*, for instance, is based on gestural sound materials while *Polyphonic Continuum* and *Musical Situation 1* are composed using textural sound materials as sustained tones and continuums. This analysis concludes that the most successful compositions are those that use textural sound materials, as the dialog between sound and space is more evident. In the case of *Topos* such a dialog is highly masked by the constantly varying sound signals, frequencies, and sound materials.

The appendix contains the experiments that constitute the basis of this research, which investigate the effects of sound localization and sound-space density variations on the perception of sound attribute, rhythm, and texture variations. Each experiment include several tests which contain a description of the objectives, a list containing the specific characteristics of the sound material used, i.e. type of sound signal, frequency, the use or not of fade in-fade out envelopes, amplitude, number of sound sources used, note duration, number of cycles of each note inside the 8-note groups, relative distance, absolute distance, relative positions, and absolute positions, and a conclusion.

The experiments are organized according to the type of sound material they use. Experiment 1 uses isolated 8-note groups with one frequency and different note durations, and investigates to which extent sound localization influences the perception of pitch, loudness, and tone color variations. Experiment 2 focuses on sustained tones, and to what extent relative position variations are able to confer sound dynamism, i.e. the perception of sound location and sound attribute variations. Experiment 3 extends the investigation on sound perception and sound localization undertaken in experiment 2 using short 8-note group impulses (attacks). The same is true of experiment 4, which uses textural sound materials, and experiment 5, which uses short sound objects created with portions of the textures created in experiment 4. The results of these experiments are described and evaluated in chapter 4.

Each experiment is accompanied by an audio file, to be found in the DVDs 1 and 2 included in appendix III. The time indication that appears next to the test number indicates the location of each test in relation to the audio file, which is presented as a Pro Tools Session with the same name as the corresponding test.

All these experiments were realized at CIME (Centro de Investigação de Música Electrónica), at the Universidade de Aveiro, Portugal, using eight loudspeakers arranged in the approximate shape of a regular octagon around the listener (see figure 19, p. 69). The distance between the loudspeakers is approximately 1 to 1,5 meters, and the distance between the loudspeakers and the subject (located at the centre of the room) is approximately 1,5 meters.

It was not necessary for the purposes of this research to consider the precise distance and position of the loudspeakers, or to manipulate acoustic space to achieve specific levels of reverberation and absorption. First, small variations in the distance and position of the

loudspeakers and listener play a role in the perception of sound attribute variations, and secondly, the spatial arrangement of the loudspeakers creates its own sound space, independently of the acoustic characteristics of the architectonic space. In addition, these tests try to emulate the conditions of a normal performance of electronic music, which imply that the positions and distance of the loudspeakers are not precisely calculated and the characteristics of the acoustic space are not taken into consideration.

Chapter 1. FUNCTIONS OF REAL SPACE IN MUSIC COMPOSITION

This chapter describes the functions of real space in musical composition, focusing on music of the second half of the twentieth century in which space is integrated as a formal element and plays a decisive role in the development of new musical aesthetics. Therefore, this chapter analyses works by Boulez, Stockhausen, Schaeffer, Ives, Xenakis, Nunes, Truax, Natasha Barrett, and Llorenç Barber, among others. We also consider how the spatial projection of call and response patterns involved in the antiphonal style used by the composers of the Venetian School such as Willaert, and Andrea and Giovanni Gabrieli; the echo and dialog effects between several choirs and orchestras used by Bach and Mozart; Berlioz's so-called “architectural music”; or the spatial separation of the musical layers with different tempi, rhythms and tonalities to achieve musical clarity and musical perspective used by Ives, Mahler, Luigi Russolo, and Darius Milhaud, are assimilated and expanded by the composers of the second half of the twentieth century.

It is not exaggerated to affirm that Stockhausen is by far the composer who most extensively investigated the possibilities of sound spatialization in music composition. Some of the spatial functions presented here are deduced from his works, as they are very well-analyzed and explained either by the composer himself or by other composers and musicologists.

It is important to mention as well, that even though each of the following spatial strategies is explained separately, in most cases they operate simultaneously and in many cases it is difficult to determine which function is more prominent or important than the others.

1.1 Formal Functions

One of the most elemental functions of space is to emphasize the echoes or dialogs inherent in the form¹⁹ of a musical composition. This strategy appeared already in the antiphonal choral music of the medieval Christian liturgy, where music is divided in two different groups placed in different locations following the call and response patterns of the antiphonal style.²⁰

The polyphonic choral music of the Renaissance retained this older technique using a smaller *cappella* choir together with the main *ripieno* choir. In the Venetian school founded by the Flemish composer Adrian Willaert, who became *maestro di cappella* of St. Mark's Cathedral in Venice in 1511, the spatialization of the choirs or *cori spezzati* was facilitated by the existence of two separate organs and choir lofts, a special characteristic of St. Mark's Cathedral. Willaert's eight-part *Vespers*, composed in 1550 is one of the earliest examples of this music and features the echo and dialogue effects between the two spatially separated groups which are typical of this aesthetic.

Andrea and Giovanni Gabrieli brought further the antiphonal style used by Willaert, developing a more rapid and sophisticated dialog between multiple choirs and instrumental groups that required a more sophisticated spatialization (see figure 1, p.29). Bryant suggests that the main choir remained at floor level so it could attend other ceremonial duties during the mass. The instrumental groups, which had no active role in the ceremony, would occupy an alternative position, most likely in the two elevated organ lofts, while the smaller *capella* choir would be placed somewhere away from the main choir. The different groups were synchronized using two additional conductors, which followed the beat indicated by the principal conductor situated at ground level with the main choir.²¹

However, Bryant points out that the choirs were not always spatially separated.

¹⁹ The term "form" refers here to both the macro and micro structures of a composition, from the division of a piece in parts or sections, which define its outer contour, to the arrangement of sounds in relation to particular frequencies (intervals), time values (rhythm), groupings (phrases), timbres or dynamics (amplitudes) (*Harvard Dictionary of Music*, 1970, Second Edition, and *The New Harvard Dictionary of Music*, 1986, The Belknap Press of Harvard University Press, Cambridge, Massachusetts, pp. 326-327 and 320-321). As it is explained in this chapter, space is introduced as another parameter involved in the outer and inner structures of a piece by assigning different sound positions and sound trajectories to the sounds.

²⁰ The term antiphon was used to denote a sung response to a psalm during a religious service, and this gave rise to the antiphonal style of singing which was widely used in medieval church music.

²¹ Bryant, D., 1981, *The 'cori spezzati' of St Mark's: myth and reality*, Early Music History, Vol. 1, pp. 165-186.

Historical records indicate that the spatialization of the choirs was only realized in some occasions as a special effect, following the requirements of a musical director or special guest.²² Indeed, call and response patterns are implied by contrasting musical materials and orchestrations, and can be perceived without using the spatialization of the individual groups.



Figure 1. Echo effect in Giovanni Gabrieli's *In Ecclesiis*

The *cori spezzati* influenced other compositions of that time, such as Thomas Tallis' *Spem in Alium* (1573) for forty-three separate vocal parts arranged in eight choirs, or Orazio Benevoli's *Festival Mass* written for fifty-three parts, two organs and *basso continuo*. The use of separate choirs and musical groups to emphasize echo and dialogue effects is also found in J. S. Bach's *St. Matthew's Passion* (1729), one of the late examples

²² Ibid., 1981, pp. 165-186.

of polychoral sacred music before the beginning of the Classical period.

During the next three hundred years this practice decreased significantly. The main reason was that the Classical and Romantic styles turned away from counterpoint to focus on homophonic music, reducing the interest in using spatial separation between the musical events. In fact, the use of the polychoral techniques such as the *cori spezzati* were associated with the *stile antico*, and “lived on to become something as an anachronism.”²³ In the period from approximately 1750 until 1900, the main preoccupation was with arranging large instrumental groups in space to achieve dynamic and timbre balance, as in the case of symphony orchestras. For instance, it was common to arrange the first and second violins next to each other, or separated by the viola and cello sections.²⁴

However, the use of separate choirs and musical groups to emphasize the echo and dialogue effects was also used. Christoph Willibald von Gluck in his opera *Orfée et Euridice* (1762) incorporates a second orchestra constituted by strings and harp positioned “derrière le theater” (off stage). This second orchestra in Act II increases the drama of this tragic opera, as it enhances the dialog (literal call and response) between Orfeo and the creatures of the underworld. The distance between the first and second orchestras depicts the distance between the underworld and the earth.

An important example of a purely instrumental spatial composition is Mozart’s *Serenade No. 8 (Notturmo) in D Major for Four Orchestras*, K. 286 (1777), in which each orchestra consists of a four-part string sections plus two horns. Although Mozart does not specify the exact position of the orchestras, he uses dynamic and thematic fragmentation to create the illusion of echo effects. As pointed out by Denis Arnold, “a short statement by the first orchestra is repeated in turn by the other three, each abbreviating the phrase until the fourth sounds only a faint fragment of it—just as an echoed shout fades out in the distance”²⁵ (see figure 2).

²³ Denis Arnold, 1959, *The Significance of ‘Cori Spezzati*, *Music & Letters* 40.1, p.14.

²⁴ *The Symphony: An Interactive Guide*, available at: <http://library.thinkquest.org/22673/orchestra.html> (accessed March 1, 2014); *The Orchestra: A User’s Manual*, available at: <http://www.mti.dmu.ac.uk/~ahugill/manual/seating.html> (accessed March 1, 2014).

²⁵ Time Magazine, 1964, *A Choice and an Echo*, available at: <http://www.time.com/time/magazine/article/0,9171,871353,00.html> (accessed March 2, 2014).

I

W. A. Mozart
1756-1791
Köchel Edition, No. 264

Andante

The musical score is arranged in four systems, each representing one of the four orchestras. Each system contains five staves: Corni in D, Violino I, Violino II, Viola, and Basso. The first system (Orchestra I) shows the initial melodic and rhythmic material. The second system (Orchestra II) introduces a 'Ersten Echo' (First Echo) in the Violino I part. The third and fourth systems (Orchestra III and IV) are currently silent in these measures.

Figure 2. Mozart, *Serenade for Four Orchestras*, first movement, mm. 1-5.

The image displays a musical score for Mozart's *Serenade for Four Orchestras*, first movement, measures 6-10. The score is organized into three systems, each labeled 'Echo' (Zweites Echo, Drittes Echo). Each system features five staves: Cor. (Coronet), Vl. (Violin), II (Violin II), Vla. (Viola), and B. (Bass). The music is in G major and 3/4 time. The first system shows the initial entry of the instruments. The second system, labeled 'Zweites Echo', shows the instruments re-entering. The third system, labeled 'Drittes Echo', shows the instruments re-entering again. The score is numbered 10 at the top right.

Figure 2 (continuation). Mozart, *Serenade for Four Orchestras*, first movement, mm. 6-10.

The use of offstage performers to create the illusion of distance, which reveal their programmatic and narrative styles, is perhaps the most pronounced spatial effect utilized during the Romantic period. In his *Symphonie Fantastique*, Berlioz creates an offstage call and response dialog between the oboe and English horn that recreates the distant piping of shepherds. Mahler uses an offstage military band consisting of four trumpets, four horns, triangle, cymbal, and bass drum in the final movement of his *Symphony No. 2* (1893–

1894). Even though Mahler does not give a detailed placement for the offstage band in the score, he does indicate that the four trumpets must sound from different directions.²⁶

With serialist composers came the development of more sophisticated formal functions of space beyond simple call and response patterns. The best example is Boulez’s piece *Répons*²⁷ (1958), inspired by medieval antiphonal choral music, which implements dialogs between the main orchestra surrounded by the audience, and the soloists, situated around the audience together with six loudspeakers (see figure 3).

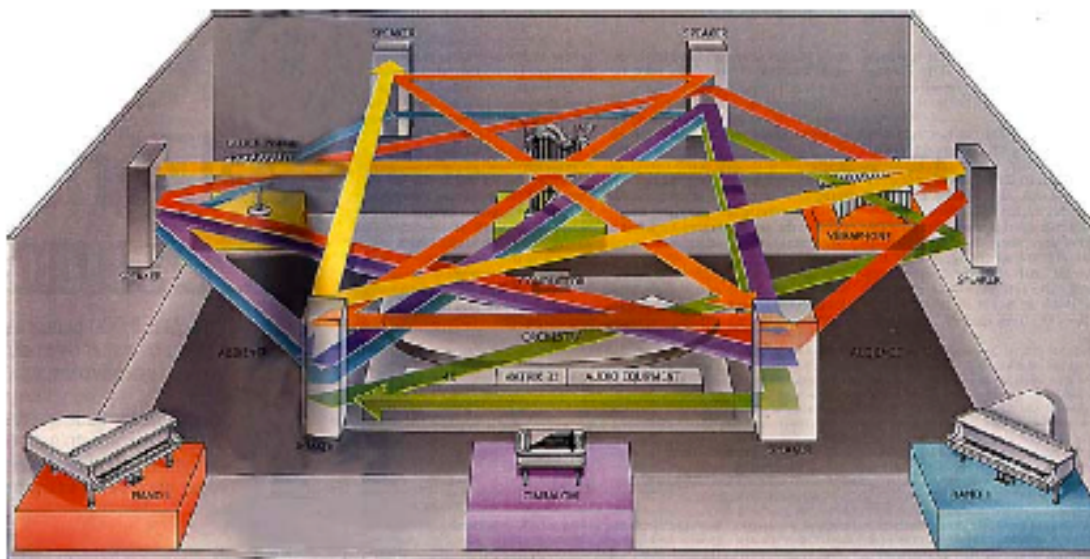


Figure 3. Position of the instrumental groups and diagram of the sound trajectories in *Répons*.

In *Répons* sound spatialization is related to the form of the piece at many levels. First, like the *cori spezzatti*, the spatial disposition of both orchestra and soloists makes the

²⁶ Mahler, Gustav, 1971 (revised version), *Symphonie II*, Universal Edition, Vienna and London, p. 175.

²⁷ *Répons* was premiered as a work in progress at the Donaueschingen Music Festival in October 1958, and represents one of the first pieces to use live performance and spatialization of electronic music. The final version was completed in 1984, and used the 4X real time digital processor for the analysis, transformation, and synthesis of sounds in real time; and the Matrix 32, a programmable audio signal traffic controller for the dynamic routing of audio signals between the instrument microphones, the 4X, and the loudspeakers. These digital systems were developed in IRCAM by Miller Puckette, Michel Fingerhut, and Robert Rowe (4X), and Michel Starkier and Didier Roncin (Matrix 32) (Häusler, J. and Boulez, P., 1985, *Pierre Boulez on Répons*, Teilton, Schriftenreihe, der Heinrich-Strobel-Stiftung des Südwestfunks, Vol. 4, pp. 7-14).

audience aware of the distance between them, as well as between the soloists themselves, which helps to illustrate and emphasize the call and response patterns. Second, the single questions formulated by the soloists are answered by multiple responses from the orchestra. This multiplicity of answers is also reflected in the spatial and temporal multiplication of single instrumental notes, which are recorded and transformed into multiple notes, chords, and timbres, and radiated through six loudspeakers following specific sound trajectories.²⁸ Figure 3 above shows each trajectory with a different color.

Third, the intention of such sound trajectories is not that they are perceived by the audience, but are used to differentiate the electronic gestures. These electronic gestures are associated with the amplitude envelopes of the instrumental gestures, which are exaggerated using different velocities for each trajectory. Each instrumental gesture has a similar envelope, i.e. a sharp attack followed by a gradual decay, which varies depending on timbre, pitch, and amplitude. The velocity of each trajectory decreases proportionally to the decay of each instrumental passage, linking the instrumental gesture of the soloist to the spatial shape of the electronic part (see figure 4).

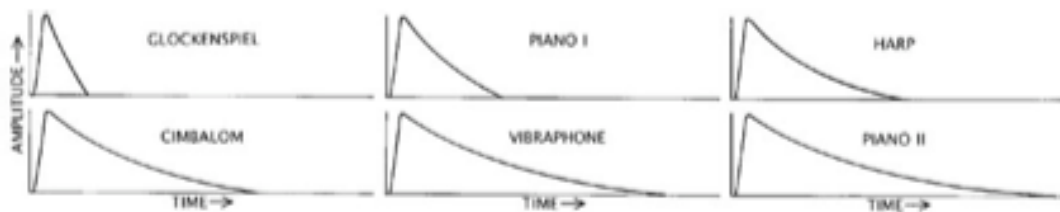


Figure 4. Amplitude envelopes of the six solo instruments in *Répons*.

Sound circulates in space using the 4X system control,²⁹ which determines sound movement by switching on and off the input signal of each loudspeaker following flip-flop modules. These modules control the time signal at each loudspeaker, which varies

²⁸ Boulez, P., and Gerzso, A., 1988, *Computers in Music*, Scientific American, Vol. 258 (4).

²⁹ The 4X system control was a digital signal processor for the analysis, transformation, and synthesis of sounds in real-time, which was designed at IRCAM by Giuseppe Di Giugno and Michel Antin (Boulez *et al*, 1988). The 4X could store, manipulate and recall up to four seconds of digital audio using various software modules, or patches, and a real-time operating system and event scheduler developed by Miller Puckette, Michel Fingerhut, and Robert Rowe.

depending on the amplitude of the waveform. Consequently, while the sound signal decays, the flip-flop module holds the signal at one loudspeaker for longer time before changing to the next (see figure 5).

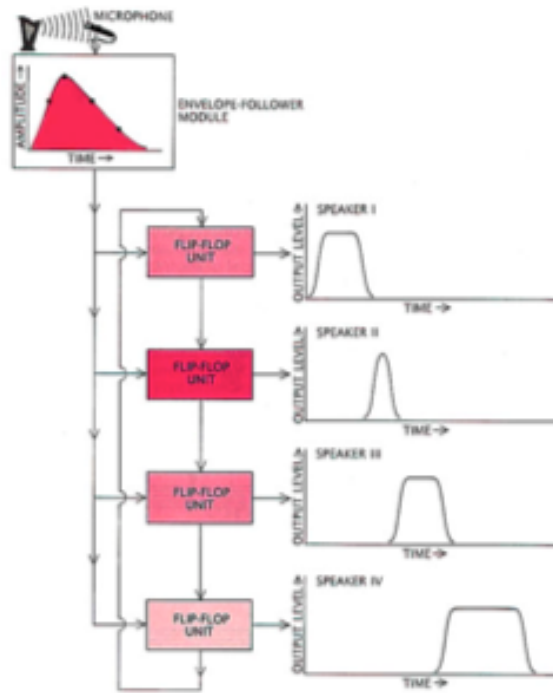


Figure 5. Spatial switch mechanism in the piece *Répons*.

Boulez also establishes a structural relationship between the instrumental and electronic parts by spreading or projecting the arpeggios played by the soloists. The figure of an arpeggio consists of the displacement of notes both in time and in the frequency domain. The spatial separation of the notes in the score is translated into the separation of the musicians in real space, as well as into temporal and spatial displacements by the electronic part. In this way, the temporal and spatial arpeggio produced by successively playing multiple copies created by the 4X is deduced from another arpeggio, the recording of the notes of a harmonic chord played sequentially (arpeggio), which is deduced at the same time from another arpeggio, namely the sequential entrances of the different soloists.

Numerous examples showing the relation between compositional space and real space can be found as well in music by Karlheinz Stockhausen. Stockhausen suggests that sound spatialization and sound movement could be used to organize and articulate different

layers of musical material, a fundamental aesthetic element in his music³⁰. As Stockhausen says:

The spatial separation of the groups initially resulted from the superimposition of several time layers having different tempi – which would be unplayable for one orchestra. But this then led to a completely new conception of instrumental music in space: the entire process of this music was co-determined by the spatial disposition of the sound, the sound direction, sound movement (alternating, isolated, fusing, rotating movements), as in the electronic music *Gesang Der Jünglinge* for five groups of loudspeakers, which was composed in 1955/56.³¹

Stockhausen's *Kontakte* (1958-60) represents the first musical work where sound spatialization and sound movement are as important as timbre and amplitude. As Helmut Kirchmeyer explains in his extensive study on this piece, "a sketch paper contains already the movement scales from 1 till 6...for all sound categories (parameters) of the pieces as space, instrument (sound family), form, speed, location and amplitude."³²

Indeed, certain spatial parameters such as direction, speed, and angular movement are part of the overall serial structure, while distance is used in a more intuitive way. To organize space in relation to the sound parameters implies that space itself can be measured according to a scale of extensions, amounts or quantities. In retrospect, Stockhausen said to Jonathan Cott, "I began to think in intervals of space, just as I think in intervals of pitches or durations. I think in chords of space."³³

In his article *Musik im Raum* (1958) Stockhausen suggests that the determination of an appropriate scale of sound directions or sound localizations should be made following auditory tests, instead of fixed proportions, as only the listening can determinate the minimal spatial extension needed to clearly differentiate between two contiguous sound locations³⁴ (see figure 6).

³⁰ Stockhausen, K., 1958 (a), *Musik im Raum*, in: *Texte zur elektronischen und instrumentalen Musik*, Die Reihe, English translation by Ruth Koenig, Universal Edition Publishing, vol. 5, 1975.

³¹ Moritz, A., 2009, *Stockhausen: Essays on the Works*, <http://home.earthlink.net/~almoritz>, (accessed April 1, 2013).

³² Kirchmeyer, Helmut, 1982/83, *Zur Entstehungs- und Problemgeschichte der 'Kontakte' von Karlheinz Stockhausen*, in: *Ansätze zur Musik der Gegenwart*, Band 3, Neuland Musikverlag Herbert Henck, Bergisch Gladbach, p. 169.

³³ Cott, Jonathan, 1974, *Stockhausen, conversations with the composer*, Robson Books, London, p. 92.

³⁴ This procedure is supported by studies on spatial hearing, which conclude that the auditory space is not as accurate as the physical space where sound sources exist, as small variations in sound location don't correspond necessarily to a change in the position of the auditory event. This phenomenon is called "localization blur" (Blauert, 1997, p. 38).

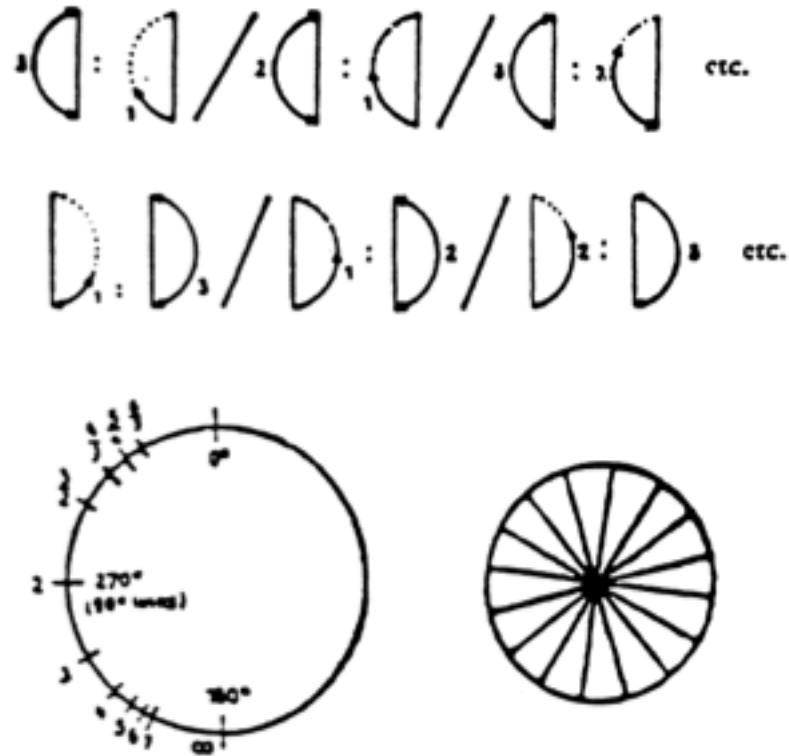


Figure 6. Spatial intervals and directions proposed by Stockhausen in *Music in Space*.

In *Kontakte*, for instance, Stockhausen works with rows that permit him to incorporate degrees of alteration to the movement of sound, such as the speed that a sound moves from one loudspeaker to another. Stockhausen differentiates between six different spatial movements: rotation, looping, alternation, static distribution with a duplicated source, static distribution with different sources, and single static sources. These spatial movements are used following different speeds and sound directions, either interacting with each other or with static locations of the acoustic instruments. The specific spatial

movement is determined by the serial method in the same way as pitch and rhythm, based on a predefined scale of speeds and spatial directions.

Differently to sound direction and speed of sound, Stockhausen considered distance

as a secondary spatial parameter, as the perception of distance is not exactly determined by the position of the sound source, but depends on other factors as the familiarity with the sound signals as well as timbre and amplitude. Therefore, distance cannot be accurately determined using the serial method. However, Stockhausen uses distance to support dynamic aspects of the music or as a dramatic element, as in the case of fast oscillating sounds used together with loud sounds, or the suggestion of spatial depth using a dense layer of material in the foreground suddenly removed to reveal a more distant layer in the background.

Consequently, composed spatiality has not only a formative function, i.e. determining the circulation or speed of movement of sounds between groups or inside individual groups, but a structural function used to develop conclusive musical sections or complexes together with other parameters such as amplitude and sound density. In Stockhausen's *Gruppen für drei Orchester*, for instance, the organization of sounds in spatial constellations is not only important for the formal development of the piece, but it has also dramaturgical consequences by influencing the musical coherence and its character. This dramaturgy is achieved by contrasting spatial criteria – successive presentations of extreme opposed sound movements and static sound situations.

The arrangement of sounds in space can be determined following certain formal aspects of the piece. This is the case of compositions such as *Percussion Quartet* (1952), *Kreuzspiel* (1951), and *Formel für Orchester* (1951) by Stockhausen, which establish a relation between sound spatialization, timbre and register. In a letter to Goeyaverts from 24.1.1952, Stockhausen explains the structural idea of *Formel für Orchester*, the derivation of acoustic spaces from the relation of the octaves of the piano keyboard: “the octaves are similar rooms in different floors (with different light conditions), where each sound object will enter once.”³⁵

“Light conditions” is used in this context as a synonym for different pitch heights, for instance low or high spectral frequencies, and “similar” refers to similar spatial extensions, in reference to the extension of an octave.

In relation to *Kreuzspiel*, Stockhausen explains the relation between timbre and sound spatialization as follows:

³⁵ Sabbe, Herman, 1981, *Karlheinz Stockhausen ... wie die Zeit verging ...*, H.-K. Metzger, R. Riehn (Hrsg.) Musik-Konzepte 19, Edition text+kritik, München, p. 24.

And the seven octaves, in which each of the twelve chromatic pitches are repeated, are for me seven spaces as seven rooms of a house. That is so clearly composed, that I have also given to each sound room a particular characteristic. So it is in *Kreuzspiel*, that the complete sound room in the middle is only occupied by the color of bass clarinet and oboe. Only these two instruments will play the notes that take place there, there are no other notes played by the piano, so spaces have also a particular color, timbre.³⁶

Sound spatialization can be even more significant for the outer form of the pieces compared to *Kreuzspiel* or *Formel für Orchester*. This is the case of *Polyphonic Continuum*, one of the three pieces presented in this thesis, where sound spatialization determines almost exclusively the outer form of the piece.

Polyphonic Continuum consists on five independent sections using a different number and combination of the same five continuums.³⁷ On one hand, the only parameter that differentiates one continuum used in one section from the same continuum used in another section is its spatial position and spatial extension. The continuums are arranged in four pre-established areas and four circles around the listener (see figure 16, p. 67). As explained in the chapter two, the position and spatial extension of sound have important consequences for the perception of sound attribute, rhythm and texture variations.

On the other hand, each continuum is formed through the successive repetition of 8-note groups with no variations in time except very long and gradual amplitude variations. Therefore, the most significant difference between them is their movement through different relative and absolute positions as well as sound-space densities, which imply sound location variations within the same area or circle as well as the perception of sound attribute, rhythm and texture variations. These aspects will be fully explained in chapter 3.

In addition, the first five sections are repeated again using the spatial inversion of each continuum³⁸ (see figure 7), so sound spatialization is the only parameter that differentiates the first five sections from their repetition.

³⁶ Nauck, 1997, p. 181, excerpt of an interview between Nauck and Karlheinz Stockhausen in 1992 (translated by the author).

³⁷ For an explanation on what continuums are please see subchapter 4.2.2.1.

³⁸ The structural and formal organization of *Polyphonic Continuum* is described in more detail in chapter 5.2.

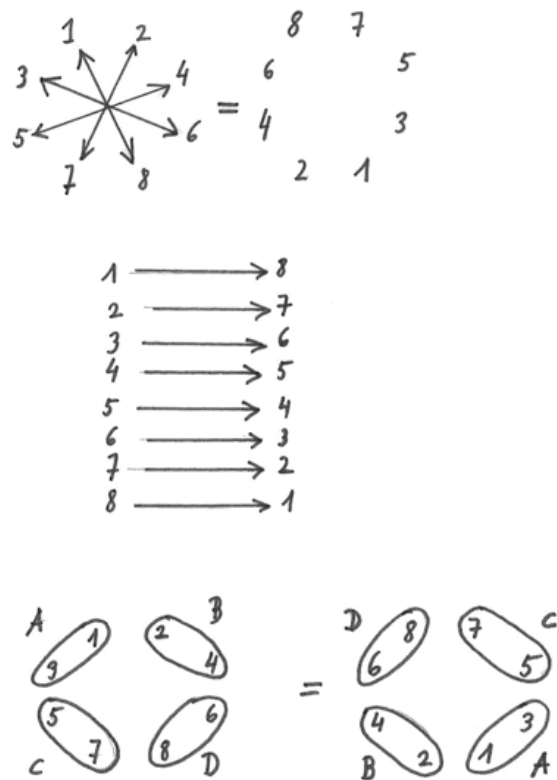


Figure 7. Spatial inversion of notes, areas and circles.

In *Polyphonic Continuum*, a dramatic effect similar to *Gruppen* is achieved, by using contrasting spatial sound densities and sound extensions between sections. In *Polyphonic Continuum*, section 6 contrasts dramatically with the above-mentioned spatial and dynamic climax of section 5, as it drastically changes from the greatest sound density (5 continuums) spread in space using the maximum sound extension (5 circles) to a single continuum spread in space using the spatial extension of one area only.

All these spatial variables, namely sound location, spatial extension, sound movement, relative and absolute positions, and sound-space density, are not only important to define the outer and inner form of the piece, but also have important consequences for the perception of sound attribute, rhythm, and texture variations. These phenomena are explained in detail in chapters 2 and 3.

Another example that illustrates the relation between the form of the piece and the perception of sound is found in the composition *Musical Situation 1*, where the speed of movement of the notes in the 8-note groups from one spatial position to another is

determined by the note durations. The shorter the note duration, the higher the velocity. At the same time, note durations are proportional to frequency, as lower frequencies, for instance, have longer note durations compared to higher frequencies.

As in *Répons*, in *Musical Situation 1* it is not intended that the sound trajectories of the notes in the 8-note groups are perceived. On the contrary, the use of different relative positions avoids the recognition of recurring sound trajectories, and helps to create homogeneous textures. Depending on the amplitude level of the layers, these homogeneous textures create diffuse sound fields. As explained in subchapter 2.7, the perception of diffuse sound fields implies the impossibility of determining the sound source locations.

Sometimes, however, it is possible to recognize rhythmic patterns and sound trajectories by manipulating the amplitude levels of some notes in the 8-note groups. In these cases, it is possible to achieve both sound directionality and the perception of rhythmic dialogs between different layers, including the effect of “sound relief” proposed by Schaeffer (see subchapter 1.5). Indeed, the recognition of sound trajectories permits differentiation between different simultaneous layers and the creation of spatial perspective. This phenomenon is largely used in *Musical Situation 1*, with the additional characteristic that such sound trajectories are accompanied by the perception of important pitch, loudness, and tone color variations.

1.2 Musical and Sound Transparency

Another important function of sound spatialization is to achieve musical clarity and transparency, especially when music presents different layers with different rhythmic structures, tonalities, and tempi. Studies on spatial hearing undertaken by Shinn-Cunningham support this strategy used in musical composition, as they prove that sound spatialization is highly important for the intelligibility of multiple speech signals presented simultaneously.³⁹

In addition to sound spatialization, the possibility to differentiate an audio scene into

³⁹ Shinn-Cunningham, B. G., 2003, *Spatial hearing advantages in everyday environments*, in: Proceedings of ONR Workshop on Attention, Perception, and Modelling for Complex Displays, Troy, New York, (cns.bu.edu/shinn/pages/spatial.html) (accessed December 2012).

multiple distinct components is also important to segregate and follow each individual sound signal from multiple streams, which is referred as “cocktail party effect”.⁴⁰ The Auditory Scene Analysis (ASA) proposed by Bregman indicate that in the process of differentiation, the auditory system evaluates the level of coherence and incoherence between sound signals (see subchapter 2.6.1), and establishes correlations based on similarities in relation to pitch, amplitude, timbre, and sound location.⁴¹ These studies explain why it is possible to follow a musical discourse formed by different simultaneous melodies and rhythms.

The first clear example in the twentieth century where sound spatialization is used to clarify the perception of different musical layers is the Charles Ives' *The Unanswered Question* (1908). In this composition, each layer is differentiated by a different timbre, tempo, tonality, and dynamic. First, the string orchestra performs slow, sustained *ppp* tonal triads throughout the whole piece. This continuous flow is sporadically interrupted by an atonal *p* melody performed by the trumpet, which represents the question. The question is answered by the woodwinds, which perform several simultaneous unrelated melodies in different tonalities, indicative of an unanswered question, which appear different times using dynamics from *p* to *fff*.

Regarding sound spatialization, the string orchestra is situated off-stage and around the audience, the trumpet somewhere at a distance, while the woodwinds occupy the stage. To be sure, the perception of each layer is improved through the use of sound spatialization, as it permits one to differentiate and isolate each layer more easily, and to perceive the individual melodies and rhythms independently from the others when they are played simultaneously.

Other composers who experimented with simultaneous and unrelated musical layers

⁴⁰ Blauert, 1997, pp. 257 and 275.

⁴¹ Auditory Scene Analysis describes the variables that permit the auditory system to differentiate different sound signals in an auditory situation, and are based on the Principles of Perceptual Groupings. This principles are defined as 1) the *principle of proximity*, which relates elements that are positioned close together, 2) the *principle of similarity*, which relates sounds with similar pitches and timbres, 3) the principle of *good continuation and completion*, which relates events that occur continuously following each other, and 4) the *principle of common fate*, which relates events with the same frequency, dynamic, and rhythmic coherence. These groupings are defined by Bregman as *primitive segregation*, and represent a first analysis of the auditory events. A second analysis is realized by the experience of the subject, and its expectations on the development of the sound signals. This second analysis is defined as *schemas* (Bregman, A. S., 1990, *Auditory Scene Analysis*, MIT Press, pp.196-200, 204-250, 455-490).

use this strategy with the same purpose. The futurist composer Luigi Russolo (1885-1947), for instance, used sound spatialization to present a collage of different noises. Darius Milhaud (1892-1974), who composed the ballet *L'Homme et son desir* (1918) likewise used multiple spatially distributed ensembles playing independently of each other, sometimes in different meters.⁴²

The use of sound spatialization to achieve musical clarity was the first spatial function used by Stockhausen (see figure 8).

Figure 8. *Gruppen*, rehearsal number 28.

⁴² Zvonar, R., 2004, *A History of Spatial Music*, eContact, Vol. 7(4), Canadian Electroacoustic Community.

Like Ives, Stockhausen permits the perception of different rhythms and tempi between layers, conceived as “independent [...] action and sound times”⁴³ organized according to serial methods. Nauck points out the influence of time organization on sound spatialization when she says that “time is spatialized due to the simultaneity of polymetric, random tempi (*Zeitmaßen*) and polytempi [...] Compositions with more than one tempo require then — as in *Gruppen* — real space.”⁴⁴

In *Gruppen*, differentiation among the layers is not as evident as in the case of Ives, where each layer uses different sound materials, tonalities, timbres, tempi, rhythms, and amplitudes, which contribute to differentiate them more easily. Serial organization implies that layers are not as well-differentiated from one another, even though they are organized using different tempi and rhythmic structures.

In the example of figure 8 above, for instance, the three orchestras play simultaneously using two different tempi (rehearsal number 28). While orchestras 1 and 2 play with a tempo of quarter note = 113,5, orchestra 3 plays with a tempo of quarter note = 90. It is very difficult to perceive these two different tempi, as the rhythmic values of the melodic lines are not regular, as they use subdivisions of the quarter note that mask to a great extent the normal rhythmic pulses dictated by the tempo. There are also no important differences between the three simultaneous layers that permit one to differentiate them, as they use the same instrumentation, and all three orchestras follow the dynamic curve that leads to a crescendo. Under these conditions, space becomes fundamental to differentiate the three simultaneous layers.

Certainly, this temporal stratification⁴⁵ demanded more distance between the musicians to be audible. Nauck points out that the inclusion of real space was needed, as the serial organization through such polyphony was reaching “the limits of aural perception and its acoustic viability.”⁴⁶

⁴³ Stockhausen, Karheinz, 1956 (b), *Zeitmaße (1955/56) für Oboe, Flöte, Englisch-Horn, Klarinette, Fagot*, in: K. Stockhausen, *Texte sur eigenen Werken und zur Kunst Anderer*. Aktuelles, Bd. 2, D. Schnebel (Hrsg.), (DuMond Buchverlag) Köln 1988.

⁴⁴ Nauck, 1997, p.194 (translated by the author).

⁴⁵ Stockhausen uses the term “functional spatial music” to designate the relation between sound spatialization and “the new form of multilayer time composition for instrumental music” (Stockhausen, 1958, *Gruppen für drei Orchester*, Werk Nr. 6 (1955-57), in: K. Stockhausen, *Texte sur eigenen Werken und zur Kunst Anderer*. Aktuelles, Bd. 2, D. Schnebel (Hrsg.), DuMond Buchverlag, Köln, 1988).

⁴⁶ Ibid., p.187.

The spatialization of the different layers helped as well to provide musical transparency or musical perspective, which was lost due to the disappearance of the hierarchy between the notes imposed by the serial system. In tonal music, for instance, musical perspective is achieved by using very recognizable melodic lines above the accompaniment or other contrapuntal lines, which are differentiated from one another by contrasting timbres, registers, rhythms, and dynamics. This problem is pointed out by Stockhausen, who's use of the term *transparency* in music draws from painting. As Nauck says:

(Transparency) conduces his understanding toward the function, similar to painting – and Stockhausen refers to Paul Klee as an example – to provide a composition with various perspectives from inside out. This new perspective consciousness is insofar meaningful, because through the serial organization the traditional foreground-background relations were lost. Spatialization enabled a new plasticity of music.⁴⁷

Besides serial music, other music presents complex polyphonic textures that demand sound spatialization. This is the case, for instance, of Emmanuel Nunes' *Quodlibet* (1991) or *Lichtung II* (1996) and *III* (2007). *Quodlibet* uses, like *Gruppen*, different layers with different tempi. The simultaneous tempi are only recognizable when each layer is spatialized. Otherwise, the different layers with different tempi are perceived as a complex single layer. Without sound spatialization the listening becomes rapidly saturated due to the amount and diversity of musical events. This saturation is very much attenuated through sound spatialization. The more space is used between the groups the more clarity and transparency is achieved,⁴⁸ and the listener can more easily isolate particular musical events from the others and construct his or her own musical discourse out of the whole. At the same time, the listener can recognize and follow the spatial dialogs created by those

⁴⁷ Ibid., p.236.

⁴⁸ Besides Coliseu dos Recreios (1992), *Quodlibet* was also performed in the Salle Wagram in Paris (1992), with important consequences for musical reception. For instance, the distances between the orchestra and the sub-groups was not so pronounced, which masked the auditory distinction of the different instrumental groups, perceiving the superposition of different tempi not as stratified but as one complex rhythmic situation. In this case the tension due to the confrontation of two contrasting situations was heard as one global flux. In addition, the dimensions of the Coliseu are much bigger than the ones in Wagram, which involved that, besides the change from the three planes of height in the Coliseu to two planes in Wagram, all the contrasting distances so important for the spatialization (the 'near' versus 'far') were turned to one homogeneous distance for all the sound sources.

musical elements without much difficulty.⁴⁹

Other examples of sound transparency are those offered by Natasha Barrett, who uses pure electronic sounds and loudspeaker arrays (orchestras of loudspeakers⁵⁰) to separate the frequencies of sound into its various components, so they can be perceived separately. Barrett illustrates this process with a number of audio examples.⁵¹ In the first example, for instance, eight continuous sounds with a significant degree of temporal and textural similarities are played simultaneously at static points in space while in the second example each sound is dynamically moved in space. Barrett suggests that only five distinct sources are perceivable when positioned at static spatial locations, and the number increases when each source is provided with individual and dynamic spatial trajectories. This approach to sound spatialization was developed by Pierre Schaeffer already in 1952, who introduced the idea of “sound trajectories”⁵² to create a musical relief through the contrast between static and moving sounds.⁵³

Sound clarity and transparency is also an important function of space in the compositions presented in this thesis. On one hand, in *Polyphonic Continuum* several continuums are played simultaneously. Even though each continuum is differentiated by a

⁴⁹ Even though I never had the opportunity to hear a live performance of *Quodlibet*, I listened to *Lichtung II and III* in a concert in Casa da Música in Porto in 2011 and experienced how the saturation of sounds and musical elements perceived when listening to the stereo version disappeared to a great extent when listening to the spatialized version. In addition to sound clarity and transparency, it is possible as well to perceive the sound space created by sound spatialization and the electronically manipulated echoes of real instruments.

⁵⁰ Differently to the loudspeaker arrays used by Stockhausen, the loudspeaker orchestra consists of diverse types of loudspeakers with different frequency ranges, used to separate the spectral characteristics of sound. The use of the loudspeaker orchestra implies a musical aesthetic that focuses on the temporal, spectral and spatial development of sound, using the loudspeaker arrays to accommodate sound to particular architectural spaces, and to potentiate particular characteristics of sound and music. At the same time, the loudspeaker orchestra permits presenting stereo signals in big spaces to big audiences, so it is optimally perceived. This approach was developed at GRM (Group de Recherche Musical), the collective founded by P. Schaeffer and P. Henry in 1958. The first formalized system of loudspeaker arrays was developed by the composer and technician François Bayle, who took charge of the GRM in 1966, and the engineer Jean-Claude Lallemand as a continuation of the *potentiomètre d'espace* developed by Jacque Pullin (Gayou, E., 2007, *The GRM: landmarks on a historic route*, Organised Sound, Vol. 12(3), Cambridge University Press, pp. 203–211). The source material is generally a stereo signal routed to a mixing desk, which permits to route the stereo track to different loudspeaker pairs. This approach developed by Henry and Bayle was adopted by other institutions, such as the *Group de Musique de Brouges* in Belgium, or the *Birmingham ElectroAcoustic Sound Theatre* (BEAST) at the University of Birmingham, and composers such as D. Smalley and N. Barrett among others.

⁵¹ Barrett, N., 2003, *Spatio-Musical Composition Strategies*, Organized Sound, Vol. 7(3), p. 313-323.

⁵² Schaeffer, P., 1952, *À la Recherche d'une Musique Concrète*, Editions du Seuil, Paris.

⁵³ Sound trajectories were performed for the first time in Paris in 1951, featuring multiple monophonic turntables routed to four loudspeakers positioned to the left, right and rear of the stage, and a fifth loudspeaker placed overhead. During the performance, four tracks were routed to each loudspeaker while a fifth was spatially diffused live by a performer using the *potentiomètre d'espace*, a highly theatrical system that controlled the spatial distribution of the fifth track.

particular sound signal, pitch, note duration, and relative and absolute distance, sound clarity is achieved, as with Natasha Barrett, by moving each layer in space. Certainly, each continuum is more easily recognizable when it moves through different sound locations and sound-space densities, than when it remains static. Then, they are perceived as one unique texture formed by the sum of several different continuums.

On the other hand, *Musical Situation 1* presents a new perception of sound transparency through sound spatialization based on a specific sound quality. As explained in detail in chapter 3, the sound material consists of sustained tones constituted by the sum of small sound units. These sound units are spread in space using eight loudspeakers situated around the listener. It could be said that by spatializing these fragments, each sustained tone is filled with space. Indeed, *Musical Situation 1* is perceived as very transparent and ethereal due to the space between fragments, which is determined by the distance between loudspeakers. In this sense, greater distances between loudspeakers contribute to increased sound transparency, as it is experienced that more sound transparency is achieved when the piece is performed in big halls.⁵⁴

In addition, the achievement of sound relief is an important aspect of *Musical Situation 1*, as a result of using pitched sounds together with the transient sounds that appear when the fade-in and fade-out envelopes of each note in the 8-note groups are removed (for instance from 01'00'' to 01'30''). The transient sounds produce a granular texture that is perceived as an independent surface above the pitched notes. It is clearly perceptible how a granular texture detaches itself from the pitched surface. The perception of such relief or sound transparency is especially relevant when using sound-space density 8/8,⁵⁵ which implies the maximal distance between the notes.

1.3 Time as Function of Space

Stockhausen published two articles in the German music journal *Die Reihe* entitled

⁵⁴ This became clear when the piece was first performed in the concert hall at the Universidade de Aveiro, or at the H-104 Saal at the Technische Universität Berlin, compared to the space of the studio at CIME (Centro de Investigação de Música Electrónica) at the Universidade de Aveiro.

⁵⁵ See subchapter 3.2.

...wie die Zeit vergeht...⁵⁶ (...how time passes...) and *Musik in Raum*⁵⁷ (Music in space), where he discusses sound motionlessness and sound continuity as problems of serial music.

First, the extensive use of the serial methodology may imply the constant change of every sound parameter, which results in a rather static, pointillist texture. Certainly, in opposition to the teleological time flow, which represents the sum of the successive instants toward an end in a directional way involving cause-effect relations, the perception of temporal stillness occurs when successive sound events are not immediately deduced from the previous ones, as often occurred with the serial organization of the sound parameters. Music stops or music fades into space⁵⁸ as the directed temporal musical development is dissolved.

The second inconvenience considered by Stockhausen was the impossibility to articulate long time-phrases, as serialism prevents one parameter to remain constant and dominate, which is necessary to create musical continuity. Stockhausen suggests that sound spatialization can be used to organize sound material in longer time-phrases, as well as to clarify the complex relationships between the different layers. Therefore, the permanence and change of the musical events in space defines the temporal structure of the piece.

Similarly, spatial movement can also be related to rhythm and sound duration. In *Kontakte*, for instance, the series of spatial movements, i.e. rotation, looping, alternation, static distribution with a duplicated source, static distribution with different sources, and single static sources are treated in the same way as frequency and rhythm using a system based on the change in speed and angular direction. In this way, Stockhausen equates the spatial movements with rhythm, arguing that changes in spatial location can articulate durations in exactly the same way.⁵⁹

⁵⁶ Stockhausen, K., 1956 (a), ...*Wie der Zeit vergeht...*, in: *Texte zur elektronischen und instrumentalen Musik*, Die Reihe, English translation by Ruth Koenig, Universal Edition Publishing, vol. 5, 1975, pp. 59-66.

⁵⁷ Stockhausen, K., 1975, pp. 67- 82

⁵⁸ Stockhausen defines this motionlessness both as “Moment form”, “undirected relations where the movement congeals” or “infinite form” (unendlich Form) (Stockhausen, Karlheinz, 1960, *Momentform. Neue Zusammenhänge zwischen Aufführungsdauer, Werkdauer und Moment*, in: K. Stockhausen, *Texte zur Elektronischen und Instrumentalen Musik*, Bd. 2, D. Schnebel (Hrsg.), DuMont Buchverlag, Köln 1988, pp. 189-191), in which “every present counts little or nothing at all (...) every now...is personal, independent, centered” (Ibid, p.199).

⁵⁹ Cott, J., 1974, p. 92.

The case of *Musical Situation 1* and *Polyphonic Continuum* is similar, as the disappearance of time flow through sound signals without changes in timbre, and a musical discourse based on sound attribute and texture variations derived from amplitude and sound location variations only, direct the listener's attention to the consequences of sound movement in space. Time is perceived in relation to the spatial permanence of a sound in a particular position in space, or the duration of movement between two points in space.

As a consequence, the listening remains in a perpetual dynamic present, which is the result of the perception of a static narrative discourse in time versus a dynamic movement of sound in space. The perception of temporal motionlessness in music is discussed later in chapter 5.3, when describing the composition *Musical Situation 1* presented in part 2 of this thesis.

1.4 Opening the Musical Discourse to Multiple Perspectives

Polyphonic Continuum opens the musical discourse to multiple perspectives, as it allows the listener to move freely around the room. Each listener can approach a specific area altering the amplitude relations with other sustained tones occurring at other areas (see figure 16, p. 67), as well as focusing on one layer to better perceive the effects that different sound-space densities have on the perception of sound attribute, rhythm, and texture variations. At the same time, the movement of the listener confers a degree of indeterminacy to the composition, as it permits each listener to build his or her own musical discourse.

This indeterminacy has been developed since the beginning of serial music. Stockhausen's *Ensemble* (1967), for instance, revolutionized the communicative form of concerts through its underlying spatial model,⁶⁰ as it marked the relativization of the fixed form, and lead to the experience of open forms “so that a new openness of the hearing with a plurality of perspectives [is achieved], and music [is] perceived as well as a new acoustic communication between musicians and listeners.”⁶¹

⁶⁰ The piece involves twelve composers from six different countries, and was conducted by Stockhausen during the International Summer Course for Contemporary Music at Darmstadt (from 6/8—28/8/1967). The premiere took place on August 29th, 1967 in the Ludwig-Georg Gymnasium Darmstadt with the collaboration of the ensembles Hudba Dneska, Bratislava (direction by Ladislav Kupkovic), Aloys Kontasky (Hammond-Organ), as well as Harald Bojé, Petr Kotín, David Johnson und Alden Jenks (mixing boxes).

⁶¹ Nauck, 1997, p. 196.

In relation to serial music, this openness represents a liberation of music from the strict determinacy. Through this “collective” compositional process, “music fluctuates between the complete isolation of the individual events and the total dependence of all layers as well as between the extreme determinacy and unpredictability.”⁶²

Stockhausen’s pieces *Ensemble*, *Musik für ein Haus*, *Musik für die Beethovenhalle*, employ the spacing of the instruments and ensembles both onstage and offstage. As a consequence of the spatial separation of performers and ensembles, the compositional processes are not as important as the resulting relations produced by the interaction between the listener and the spaces. Thus the listener can decide the order and relation of the musical events in the microstructure, by choosing specific musical events from the whole and connecting them to others occurring at different spaces. At the same time he can determine the form of the piece in the macrostructure deciding which rooms he visits first, when entering or leaving the rooms, and when to interrupt the listening.

The open forms that resulted from spatialization were followed by the use of non-deterministic musical notation such as intuitive music, which use verbal scores whose interpretation is left to the performers. In this case, space becomes a reflection of the liberation of form from compositional determinism: “By Stockhausen, the compositional liberation of the brackets of the musical determinacy found an equivalent in the release of music in space.”⁶³

As already mentioned, in *Polyphonic Continuum* a certain indeterminacy of the musical discourse is also achieved, as the listener can freely move inside the concert room, approaching any of the four specific sound areas and loudspeakers. In doing so, he or she can concentrate on one particular sustained tone or area, and better appreciate the sound attribute, rhythm, and texture variations produced as a consequence of sound movement. The movement of the listener implies that each listener creates new amplitude relations between layers, redefining the amplitude balance between the sustained tones created by the composer.⁶⁴

⁶² Gehlhaar, Rolf, 1968, *Zur Komposition Ensemble*, Darmstadt Beiträge zur neue Musik, Bd. XI, B. Schott’s Söhne, Mainz, p. 8.

⁶³ Nauck, 1997, p.201.

⁶⁴ In relation to *Polyphonic Continuum*, this function of space is explained in detail in chapter 5.2.

1.5 Molding Sounds in Space: Shape and Directionality

Another important function of space is to supply a particular shape and directionality to the musical elements by moving sounds in space. This strategy is extensively used by Xenakis, who takes the idea of spatial trajectories proposed by Schaeffer and creates sonic images of geometrical shapes using both acoustic instruments and loudspeaker arrays. For instance, one single sound projected successively through a circular array of loudspeakers suggests the geometrical shape of a circle, while many short impulses radiated through groups of loudspeakers would produce the image of a sonic surface.

Xenakis differentiates between the spatialization of sounds using a *stereophonie statique*, which refer to the use of fixed sound sources, and the use of multiple mobile sounds called *stereophonie cinématique*. Similar to the idea of spatial relief proposed by Schaeffer, Xenakis suggest that the spatial forms and patterns resulting from these two types of spatialization can be used to create a spatial counterpoint.⁶⁵ Xenakis applies these two types of sound spatialization in *Terretektorh* (1965-66). In this composition, different groups of instruments are arranged in eight concentric circles (see figure 9). To discourage frontal perception, the audience is situated amongst the performers. With this organization of instrumental groups and their arrangement in particular sound locations, Xenakis tries to create a musical form based on five different sound trajectories and geometrical patterns:

- 1) stochastically distributed points
- 2) sound planes with internal movement
- 3) static sounds
- 4) densely woven individual lines
- 5) continuous glissandi.

⁶⁵ Harley, M.A., 1998, *Music of Sound and Light: Xenakis's Polytopes*, The MIT Press, Vol. 31(1), pp. 55-65.

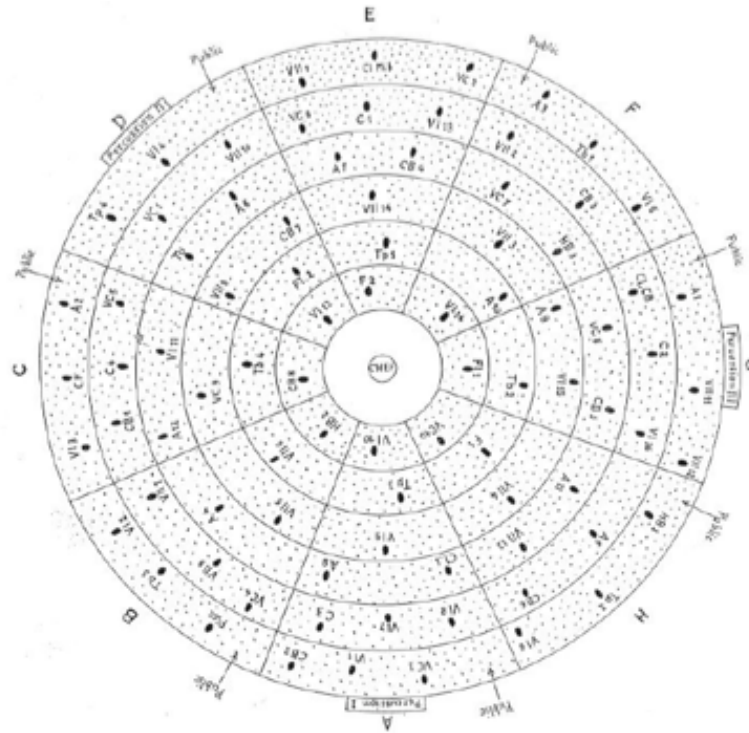


Figure 9. Spatial arrangement of instruments and audience in Xenakis' *Terretektorh*.

In relation to electroacoustic music, Chowning created computer programs that permitted him to move sounds in space and create sound trajectories. These sound trajectories were first controlled manually, although later he created a computer program that could modulate the movement of sound following Lissajous functions.⁶⁶ As Chowning explains:

In the summer following *Sabelithe* (1971) I wrote the dynamic space program including the Doppler Shift so that the sound-path could be controlled by a function. An engineer had built a little arm that had a pot at two positions so that you could move this arm and it would move a pointer on the screen, like a modern day *mouse*. He helped me to write a program to plot the points, and from that I figured out how to generate Doppler Shift on the basis of distance between points. I thought the nicest thing would be to do it manually, but finally I decided that the Lissajous-figures were much more beautiful. I was trying to draw something, with this arm, when an engineer next to me said “*Oh, it looks like if you did that maybe as a Lissajous figures...(.)*”. He explained that any phase relationship between a sine and cosine projection generalizes to a Lissajous figure (...) I experimented with these Lissajous functions, they were so beautiful. And I

⁶⁶ See footnote 16, p. 20.

made double Lissajous, I simply tried, not knowing what would happen and they were even more beautiful. So that's what I used in *Turenas* (as functions for spatial paths of the moving sounds). And they were much more graceful than I could have imagined or done by just drawing with a mouse. And once they existed, they became very much part of what I could imagine.⁶⁷

Figure 10 shows an example of a Lissajous figure used in his piece *Turenas* (1972).

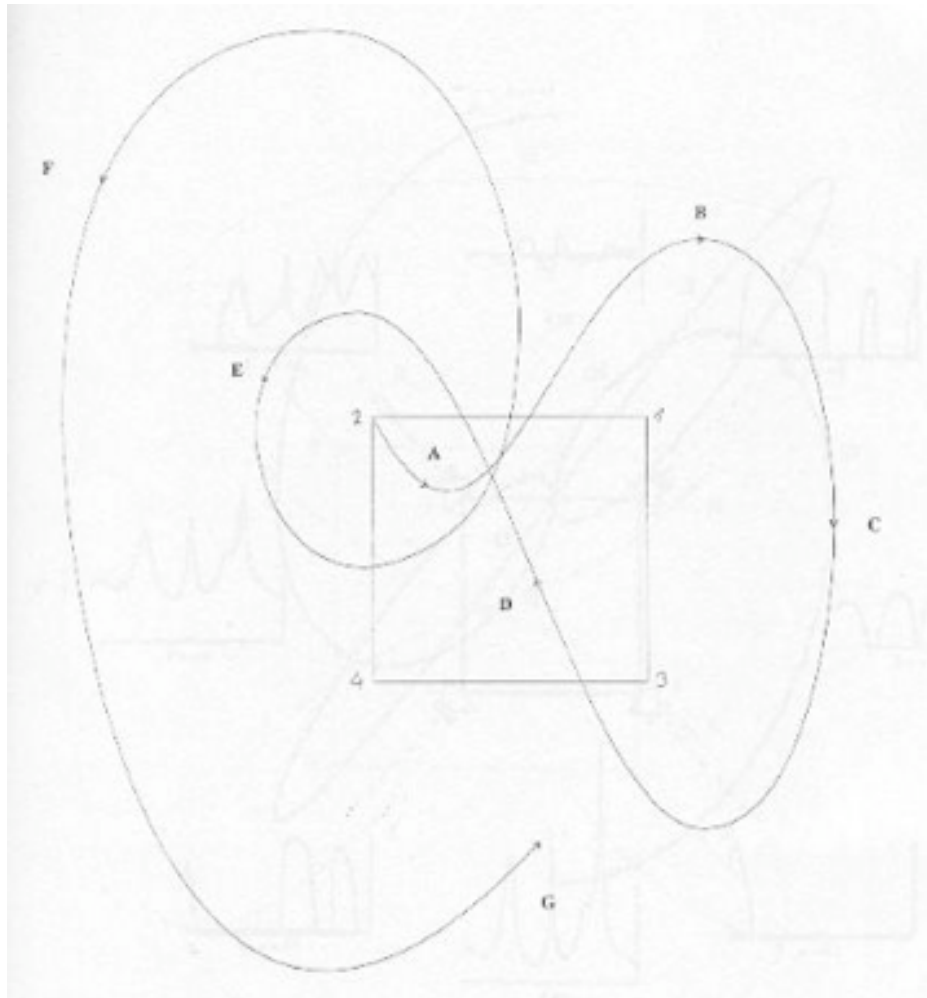


Figure 10. Lissajour figure n. 1 of the piece *Turenas* (time 00'26''- 00' 34'')

The letters follow the movement of sound. As it can be seen, the sound moves both inside and outside the area created by the four loudspeakers.

⁶⁷ J. Chowning in an interview with Bijan Zelli on Juni 3, 1998 (Zelli, B., 2001, *Reale und virtuelle Räume in der Computermusik*, Doctoral dissertation, Unpublished, Berlin, p. 169).

The pieces presented by Stockhausen at the World's Fair at Osaka in 1970 articulate both horizontal and vertical spatial trajectories (periphonic) using fifty-five loudspeakers arranged in seven rings above and below the audience. In this case, like the live diffusion practiced by Schaeffer using the *potentiomètre d'espace*, spatial movement is controlled manually. As Stockhausen explains,

I can create with my hand – up to six or seven revolutions a second. And you can draw a polyphony of two different movements, or let one layer of sound stay at the left side, then slowly move up to the centre of the room, and then all of a sudden another layer of sound will start revolving like mad around you in a diagonal circle. And the third spatially polyphonic layer will just be an alteration between front-right and back-left, or below me and above me, above me and below me, alternating. This polyphony of spatial movements and the speed of the sound become as important as the pitch of the sound, the duration of the sound, or the timbre of the sound.⁶⁸

Indeed, with the inclusion of sound spatialization and sound movement, the space can be considered a fifth dimension in the metaphorical or intended multi-dimensional space of sounds. Real space is integrated as a formal element of the composition, together with the metaphorical “four-dimensional space of sounds, i.e. lengths (durations), heights (frequencies), amplitude (loudness), waveforms (timbres).”⁶⁹

In addition to sound spatialization, sound movement permits one to “mold the direction and the movement of sounds in space and to develop a new dimension of musical experience.”⁷⁰ Stockhausen describes how the initial spatial arrangement of the orchestras and instruments permitted him to consider other spatial possibilities like sound movement:

The spatial separation of the groups initially resulted from the superimposition of several time layers having different tempi – which would be unplayable for one orchestra. But this then led to a completely new conception of instrumental music in space: the entire process of this music was co-determined by the spatial disposition of the sound, the sound direction, sound movement (alternating, isolated, fusing, rotating movements, etc), as in the electronic music *Gesang Der Jünglinge* for five groups of loudspeakers, which was composed in 1955/56.⁷¹

⁶⁸ Cott, J., 1974, p. 96.

⁶⁹ Stockhausen, Karlheinz, 1975 (a), p. 153.

⁷⁰ Stockhausen, Karlheinz, 1952-53, *Arbeitsbericht 1952-53: Orientierung*, in: K. Stockhausen, *Texte zur Elektronische und instrumentalen Musik*, Bd. 1, D. Schnebel (Hrsg.), DuMont Buchverlag, Köln 1988, p. 37.

⁷¹ Moritz, A., *Stockhausen: Essays on the Works*, <http://home.earthlink.net/~almoritz/>, (accessed on

Therefore, sound spatialization means the expansion of compositional sound events in the two dimensions of the horizontal plane, defining distance and direction in all possible 360° angles around the listener. As Nauck says, “Stockhausen defines ‘sound location’ as the fifth parameter, and outlines the resulting structural as well as formal consequences (*formprägenden*) for the composition.”⁷²

Sound movement can be differentiated into two types: continuous and discontinuous. Continuous sound movement means that the sound moves continuously from one point in space to another. This is achieved by physically moving the sound source, which can be either a performer or loudspeaker, and by virtually moving sounds, as achieved, for instance, by applying time or level differences to a sound signals radiated by two loudspeakers, as occurs with stereophonic sound systems. Discontinuous sound movement refers to those cases where sound jumps from one point to another with no sound in between.⁷³

Both sound movements create a recognizable spatial and temporal directionality. On one hand, through discontinuous sound movement, the consecutive appearances of previous events over long spatial distances give the spatial sound experience a clear temporal direction. Stockhausen speaks of “strictly directional time lines.”⁷⁴ Special cases are space melody (*Raummelodie*) or timbre melody (*Klangfarbenmelodie*), which involve a spatial aspect in contrast to the traditional melody played by one instrument only. By moving sounds across the space, sound movement becomes a dynamic element, similar to the metaphorical dynamic movement of melodies, harmonies, dynamics, etc. achieved in the traditional sense.

The continuous or discontinuous spatial movement of melodies and mass structures as chords or textures create as well a spatial rhythm, which becomes a function of space⁷⁵. The rhythm resulting from sound spatialization molds a shape to the musical elements, as “sound shape has the spatial characteristic recorded in itself.”⁷⁶

21/10/2013).

⁷² Nauck, 1997, p. 235 (translated by the author).

⁷³ The differentiation between continuous and discontinuous sound movement is mentioned by Emmanuel Nunes in his essays *Temps et spatialité* and *Une space de temps — ein Zeitraum* (in: Emmanuel Nunes: *Recueil de textes*, 1995, Ircam-Centre Pompidou).

⁷⁴ Stockhausen, 1956, p. 46.

⁷⁵ cf. Cott, 1974, p. 201.

⁷⁶ cf. Nauck, 1997, p. 228.

Spatial shape and sound directionality are better perceived when the form of the musical elements, i.e. melodies, harmonies or textures, don't move, namely that they present few or any temporal variations in relation to frequency, amplitude, rhythm or timbre. When this occurs, the attention can focus on the movement of sound in space and perceive its consequences. This is the case, for instance, of measures 46 to 54 of Stockhausen's *Gruppen für drei Orchester* (see figure 11).

Figure 11. Example from Stockhausen's piece *Gruppen* showing the movement in space of one sound object.

Figure 12 shows the direction of sound movement through the three orchestras shown in the previous example (figure 11).

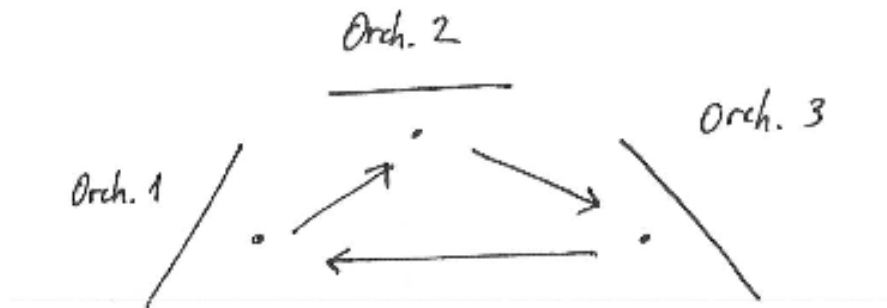


Figure 12. Direction of sound movement through the three orchestras in *Gruppen* shown in figure 11.

The cyclical movement around the audience shown in figure 12 requires that each orchestra play the identical harmonic structure with the same timbre. In this case, Stockhausen uses two chords with the notes $d\sharp'$, b' , g' , $f\sharp''$, f' , c' , and $a\sharp$, $g\sharp'$, e' , d'' , $c\sharp'$ a' in the trumpets, trombones, and horns successively. The amplitude crescendos from *ppp* to *ff* help to smooth the connections from orchestra to orchestra.

Sound movement and amplitude envelopes are also used to supply dynamism to the compositions presented in part 2. The sustained tones and continuums⁷⁷ used in *Musical Situation 1* and *Polyphonic Continuum* are molded in space following different relative and absolute positions and sound-space densities (see chapter 3). On one hand, sound-space density determines how many loudspeakers radiate the notes in the 8-note groups. Considering that the loudspeakers are located at different points in space at a certain distance from each other, this parameter establishes a relation between the number of loudspeakers used and the amount of space between the notes in the 8-note groups. When the notes in the 8-note groups are radiated by one loudspeaker, the distance between the notes is 0m (see figure 13(a)), while different distances are achieved with two or more loudspeakers (see figure 13(b)).

⁷⁷ See subchapter 4.2.1 and 4.2.2.1 respectively.

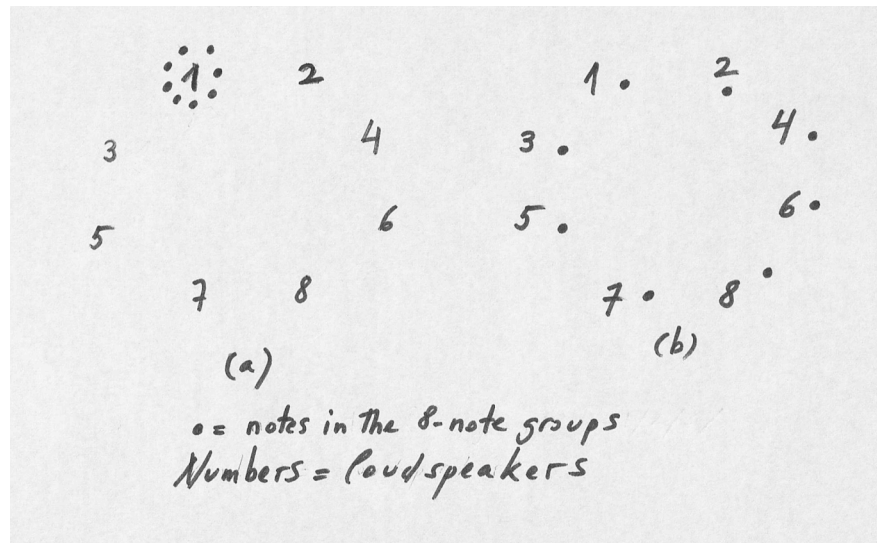


Figure 13. Representation of the spatial distance between notes in the 8-note groups in relation to the number of loudspeakers used: (a) no spatial distance, (b) with spatial distance.

On the other hand, the relative and absolute positions determine the temporal (which loudspeaker sounds first) and spatial organization of the notes in the 8-note groups (the spatial position in relation to the position of the loudspeaker). Both parameters are defined following specific rows, which are explained in chapter 3 and 4.

The sound material used for the compositions presented in part 2 use note groups involving either five or eight notes, molded in space following individual or successive relative and absolute positions as well as the sound-space densities. These parameters are very important because besides the spatial shape and directionality of the 8-note groups, they determine the perception of important sound attribute, rhythm, and texture variations, as explained in the following chapters.

For instance, the consequences of the movement of sound through different relative and absolute positions as well as sound-space densities is especially relevant in the composition *Polyphonic Continuum*, as one perceives constant variations in the shape and directionality of each continuum associated with the perception of pitch, loudness, tone color, rhythm, and texture variations.

In *Musical Situation 1*, a certain directionality is also achieved by moving the signals

radiated by one loudspeaker “continuously”⁷⁸ in space. Sound movement follows specific sound trajectories such as the ones shown in figure 14.

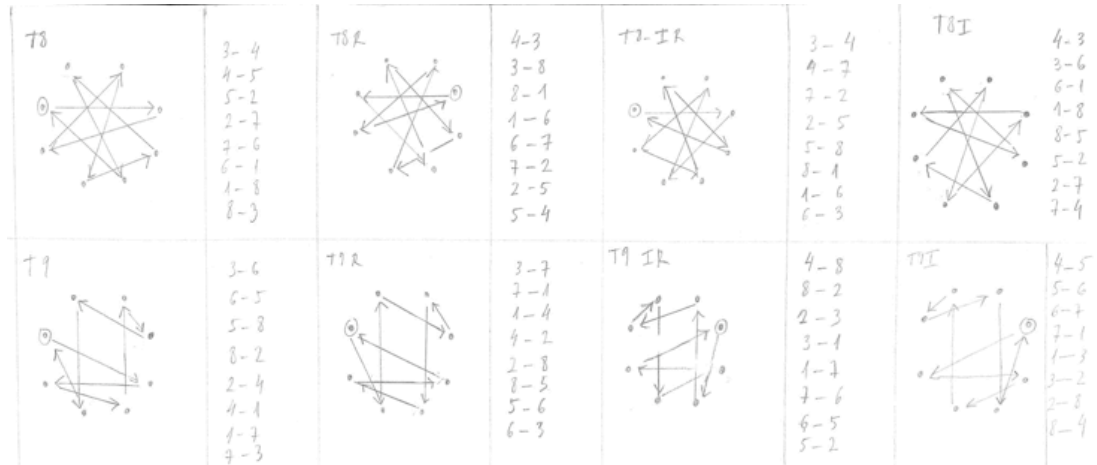


Figure 14. Example of sound trajectories used in WFS.

As in *Répons*, these sound trajectories are not intended to be perceived by the listener. Rather, the purpose of such movement is to create new and dynamic rhythmic patterns which occur when two spatially distant sound signals are brought close together. Then, instead of two independent layers with independent rhythmic patterns, they are perceived as one unique layer with a more complex rhythmic figure. The sound clarity and transparency achieved with sound spatialization (see subchapter 1.2) is deliberately avoided here. This and other consequences of the continuous sound movement are explained in detail in subchapter 5.3.6.

1.6 The Influence of Architectonic Space on the Perception of Music: Musical Space.

⁷⁸ The Wellenfeld Synthesis (WFS) permits virtual continuous sound movement between two point sources both in front of and behind the loudspeaker arrays. This system was first developed by Berkhout at the TU Delft around 1980, using the Huygens wave theory to create a system of acoustic holography using linear arrays of loudspeakers (Berkhout, A. J., 1998, *A Wavefield Approach to Multichannel Sound*, Proceedings of the 104th Convention of the Audio Engineering Society, Preprint 4749).

Architectonic spaces have important consequences for the perception of music, as they mold sounds and music differently depending on the levels of reverberation, sound absorption, and resonance. The behavior of music inside an architectonic space defines its musical space. Musical space refers to “the sound consequences formed through the acoustic characteristics of the space,”⁷⁹ which occur during the performance of a musical work in an architectonic space. Therefore, the musical space is an independent element that deforms or transforms the perception of the musical works. Nauck defines musical space as “the result of instrumental as well as electronic music performances, when the characteristics of the acoustic space are not hidden through the work, but influence the acoustic consequences of the music.”⁸⁰

Concert halls and other spaces used for the performance of music are normally designed so the levels of reflections, resonance, and sound absorption are optimal to achieve the maximal clarity for the listener. In some concert halls the musical space can be manipulated, normally by moving independent panels of the walls, so it can be adapted to a particular musical work.

In addition to sound spatialization, composers of the second half of the twentieth century were also interested in how music is transformed by the acoustic characteristics of particular architectonic spaces, finding new ways to incorporate such musical spaces to the musical composition.

Stockhausen, for instance, experimented with the relation between music and the acoustic properties of different rooms in his multi-spatial piece *Musik für die Beethovenhalle*, which included films, readings, electronic music, 4-channel loudspeaker reproductions of big orchestra and choir works (as *Gruppen für drei Orchester*, *Carré* for 4 orchestras and choir) and mixtures of electroacoustic music and the premiere of *Fresco* for 4 orchestral groups, all of them performed simultaneously in three music halls and foyers of the Beethovenhalle in Bonn.⁸¹

In these pieces, Stockhausen was worked with the resonant character of “non-neutral

⁷⁹ Winkel, Fritz, 1960, *Phänomene des musikalischen Hörens*, Max Hesses Verlag, Berlin u. Weimar, p. 55.

⁸⁰ Nauck, 1997, p. 25 (translated by the author).

⁸¹ Stockhausen, Karlheinz, 1969, *Musik für die Beethovenhalle*, in: K. Stockhausen, *Texte zur Musik 1963-1970*, D. Schnebel (Hrsg.), Bd. 3, DuMont Buchverlag, Köln 1971, p. 144.

spaces that have their own acoustic character.”⁸² In four concerts that took place in November 22-25, 1969 in the upper caves of Jeita, Lebanon, the idea was that space

has a more decisive influence on the relations between the musical outside space and “inner space” of the listeners. With its partly intuitive, partly spatially planned composed music, in addition to the bizarre acoustic of the rooms, Stockhausen wanted to transcend the rational limits in a “surrealist romantic” sense.⁸³

The use of the term “surrealistic” is not casual, as these concerts were dedicated to the figure of the surrealist painter Max Ernst. In this sense, acoustic space deforms the composed form (Gestalt) creating new temporal and spatial shapes beyond the ones proposed by the composer in the composition. Certainly, the new musical shapes and spatial forms that emerge from the interaction between the composed music and the musical space can be compared to the formal and temporal deformation of reality by the unconscious as depicted by surrealist artists.

One example that illustrates the influence of acoustic space on the compositional process is Nunes’ *Quodlibet*. In this composition, Nunes goes further than Stockhausen by analyzing the musical space before composing the piece. Nunes evaluated the temporal and spatial behavior of musical events from different locations in the architectonic space of the *Coliseu dos Recreios* using different instruments. This “auscultation” of the musical space⁸⁴ allowed him to determine the level of resonance responsible for the degree of

⁸² Ibid, p. 145.

⁸³ Ibid, p. 153.

⁸⁴ Nunes was forced to consider and study the musical space due to the extraordinary dimensions of the *Coliseu dos Recreios*, an octagonal space 40 meters long and 25 meters high. Nunes describes how sound is perceived in the parterre coming from selected locations of the architectonic space using terms as sound saturation, sound dispersion, rich in reflections etc., and points out that one of the problems of the high amount of sound reflection has to do with the difficulty of identifying the sound location of a particular sound as well as its trajectory when this sound is fragmented and dispersed in the space. As a consequence of the masking of the sound location, it is impossible to perceive its spatial course. Here are some of his descriptions:

- the stage, which occupies one of the sides of the octagon and the amphitheater: “...it sounds relatively far from the audience, as soon as the first rows are not occupied...”
- the amphitheater, first level around the 'parterre': “...provoke a very big sound dispersion.”
- the first and second boxes (loges), “...bring up a certain impression of distance and insulation.”
- the “gallery” above the boxes, the highest location, which besides the big distance in relation to the ground, is a very open place rich in reflections — specially the early ones — due to its contiguity with the dome.
- the last one is a very narrow and low corridor behind the amphitheater, which goes all the way around it. “...the sound quality becomes hollow but saturated, as consequence of a congestion of reflections”.

sound dispersion and sound definition, which would be taken into consideration to determine which instrument would occupy a particular sound location, as well as its dynamic and type of attack.

Quodlibet establishes a dialog between the architectonic space and the intended space of the composition, as the acoustic space deforms the temporal and spatial organization of sounds defined in the score. However, even in the case of *Quodlibet*, the impact of the musical space on the perception of the piece are accidental or secondary, as they occur independently of the musical work itself, i.e. the piece can be played in other spaces and still be considered the same piece.

Musical space is also important in relation to spatial hearing, as reflections have a significant influence on sound perception. Both the experiments and the compositions presented in this thesis are realized and performed in enclosed spaces, so musical space has an influence on how sound or music is perceived. However, the studios and concert halls where these experiments and compositions were performed present a very neutral musical space, so they are designed to have little influence on the perception of music.

Still, the influence of the reflections is in some cases especially important, as for instance in the perception of individual 8-note groups with short note durations. In these special cases, certain notes in the 8-note groups are completely masked by the early reflections, as it explained in detail in chapter 2 and 3.

However, it is important to mention that the perception of sound attribute, rhythm, and texture variations studied in this thesis occur independently of the specific characteristics of the musical space, as they are produced by radiating sounds through different sound locations and sound-space densities using multiple sound sources. This is the case, for instance, of the diffuse sound fields explained in subchapter 2.7. Although the reflections involved in the musical space participate in the creation of such diffuse sound fields, they occur independently of the amount of reverberation. Instead, the sufficient amount of superposed sound signals with different levels of incoherence (which are implicit in the perception of diffuse sound fields) is here achieved by time, phase, and level differences occurring when radiating the notes in the 8-note groups through eight sound sources placed around the listener. In this case, the formal organization of sound and the spatial disposition of the sound sources permit this particular “sound space.”

1.7 The Creation of Sound Spaces Using Multiple Sound Sources.

Sound can create its own space in different ways. First, sound spaces can be determined by arranging multiple loudspeakers, as well as solo or instrumental groups, in space. The listening defines an imaginary space through the “static sound position determinations, sound movement, and sound durations.”⁸⁵ In this sense, sound space can be defined as “an autonomous space for the composition,”⁸⁶ as the composed sound space exists through the “acoustic checkout (Austasten) of the geometric spaces of the composition, whenever the musical form/ structure/ Gestalt is spatialized.”⁸⁷

In contrast to spaces imagined by architects, the imaginary sound spaces created by composers using multiple sound sources remain always indeterminate. The composer will never be able to hear in an adequate way the planned sound shapes and sound courses in his sound space, since “the position of the listeners, the sound-reflection, and the sound-absorption [...] influence the imaginary sound course”⁸⁸.

In relation to the presentation of instrumental or electronic works, it often occurs that most listeners are situated far from the center of audience, which necessarily results in a distortion of the spatial trajectories of sounds. Moore has suggested that the differences in perception among listeners are analogous to perspective distortion in photography or cinematography.⁸⁹ Although this phenomenon occurs very often in spatialized music, it raises significant questions about spatial music compositions that attempt to create and relate recognizable sound shapes and trajectories with different sound durations, as in certain works by Iannis Xenakis.⁹⁰ This “motivic” use of the space, as McNabb⁹¹ defines it, assumes that every listener perceives the movement of sounds in space clearly and unambiguously.

⁸⁵ Haller, Hans Peter, 1991, *Klang- und Zeitraum in der Musik Luigi Nonos*, in: *Die Musik Luigi Nonos*, Universal Edition, Wien, Graz, p. 39.

⁸⁶ Nauck, 1997, p. 26.

⁸⁷ Haller, 1991, p. 38.

⁸⁸ Ibid., p. 37.

⁸⁹ Moore, F. R., 1983, *A general model for spatial processing of sounds*, in: *Computer Music Journal*, Vol. 7, pp. 6–15.

⁹⁰ Or in *Kontakte* by Stockhausen, where he creates a polyphony of sound movements (see subchapter 1.5, p. 49).

⁹¹ McNabb, M., 1986, “*Computer Music: Some Aesthetic Considerations*”, in: *The Language of ElectroAcoustic Music*, Macmillan Press, pp. 146-149.

However, it is difficult to know exactly how accurate the sound spaces created by Phillips Pavilion at Brussels in 1958 or the Japanese Pavilion at Osaka in 1970. Xenakis increased the accuracy of the perception of sound movement in space using the form of audiovisual spatial music, to which Xenakis referred as the *polytope*.⁹² The polytope contains a visual element that may support the auditory spatial trajectory of sounds. Although there is very little perceptual evidence that the abstract geometrical designs suggested by Varèse and Xenakis can be reliably achieved using sounds alone, this may be possible using a mixture of sound and light such as the polytope.

This accuracy is extremely difficult to achieve using sounds only, as the listeners situated far from the center of the loudspeaker arrays perceive certain parts more than others, distorting the pretended shapes and trajectories designed by the composer. For instance, *Musical Situation 1* shows that listeners situated far from the center of the loudspeaker array perceive certain parts of the polyphonic texture louder than others, distorting completely the intended homogeneity of sound space created by the composition.

In *Polyphonic Continuum*, on the contrary, this problem seems to be solved first by using a type of sound material and sound movement that permits an open discourse: the listener can move freely in the space of the performance, approaching certain regions or spatial areas more than others. This movement permits the listener to perceive certain layers in the overall polyphonic texture more clearly, and to perceive in greater detail the relations of sound movement and sound attribute, rhythm, and texture variations which occur together with the movement of each layer through different sound-space densities.

Secondly, the imaginary sound space can be defined as well by using amplitude variations as well as synthetic delays, reverberations, and echoes. On one hand, amplitude variations create the illusion that sound is radiated from different distances, as the perception of a familiar sound signal with a particular loudness implies a spatial dimension.⁹³ On the other hand, the manipulation of sounds through delays, echoes, spectral filters, etc., creates imaginary musical spaces that have nothing to do with the acoustic characteristics of concert halls, so they create “sounding spaces subordinated to

⁹² The polytope stands from the Greek words polys, which means many or numerous, and topos, which means places, spaces or locations (Harley, M. A., 1998, pp. 55-65).

⁹³ Blauert, 1997, pp. 45-46.

the character of the sound events.”⁹⁴

Third, sound space occurs also through the perception of sounds in any enclosed or open spaces, so the attention focuses not on the temporal and spatial deformation of music through the acoustic characteristics of the architectonic space, but on the temporal and spatial behavior of sound itself. As Nauck says,

This concept stands first of all as an extension of architectonic spaces as places for the realization of music inside its architectonic limits or also those unlimited territories within an urban or natural landscape. This extension signals at the same time a change of meaning: opposite to the architectonic space, sound space is generally not an independent musical limitation (*Musikunabhängige Begrenzung*) of any musical event, but indicates the expansion (*Ausdehnung*) of the musical event itself in space and time. Music develops in real space a sound-space of its own or articulates characteristic sound regions in different sound spaces.⁹⁵

However, imaginary sound space deduced through the perception of particular timbre and reverberation implicit in sound can also be altered by acoustic space. As pointed out by Smalley,⁹⁶ the perception of such parameters is different when the sound is performed for one listener in a studio or in a large performance space. For instance, the spatial depth captured in a field recording using stereo recording techniques or produced synthetically using artificial reverberation can create sound spaces that are beyond the limits defined by the loudspeaker arrays when perceived by a single listener. When performing the same sounds in large spaces, the sound space may be altered by reverberation in real space. In the same way, the perception of spatial proximity or intimacy is very difficult to achieve when sounds are performed in large spaces.

This possibility is not studied in this thesis, as it is focused on the creation of sound spaces that permit the manipulation of sound attribute perception, independently of the acoustic characteristics of both architectonic and natural environments. The influence of architectonic spaces on music perception and its importance for the compositions presented

⁹⁴ Winkel, Fritz, 1970, *Akustischer und visueller Raum. Mitgestalter in der experimentellen Musik*, in: *Experimenteller Musik*, F. Winkel (Hrsg.), Gebrüder Mann Verlag, Berlin, p. 10.

⁹⁵ Nauck; 1997, p. 26.

⁹⁶ Smalley defines these two perceptions of the same sound objects as the *composed space* and the *listening space*. In this way, he recognizes that the spectromorphological design created by the composer can be altered by the acoustics of the room (Smalley, D., 1997, pp. 107-126).

in this thesis is explained above when defining the musical spaces, and will be explained in greater depth in chapters 2 and 3.

In relation to the creation of sound spaces using multiple sound sources, the compositions included in this thesis present 8-note groups spread in space using eight, forty, or forty-two sound sources of the WFS, which, in addition to virtually locating each sound signal at any position in space, also permits the continuous virtual movement of sounds (see subchapter 5.3). Each of the three compositions presented in part 2 use different spatial arrangements of the sound sources, so different sound spaces are achieved. In the case of *Topos* and *Polyphonic Continuum*, the space is divided into four areas and four circles (see figures 15 and 16). The four areas are spatially separated to permit the differentiation of simultaneous musical events, and at the same time to achieve sound clarity and transparency, especially when the simultaneous layers use similar musical materials, as with the polyphonic textures and continuums described in subchapter 4.3.

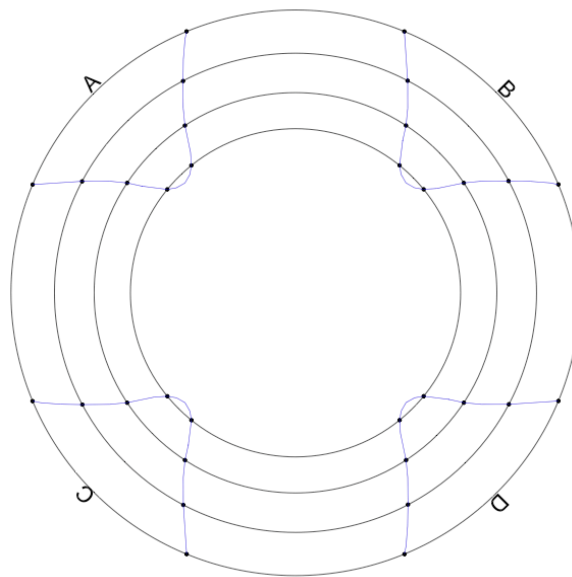


Figure 15. Sound space for the composition *Topos*.

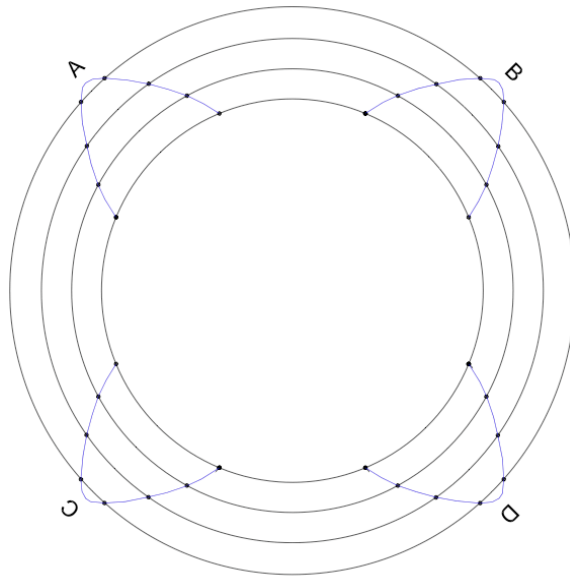


Figure 16. Sound space for the composition *Polyphonic Continuum*.

In these examples space is divided in four aural hemispheres: left-front, right-front, left-rear, and right-rear. This spatial arrangement avoids the pure front, rear, left, right hemispheres, so more ambiguity in relation to sound localization is achieved. However, even though the areas are well-defined and differentiated from one another in space, they are always ambiguous for the listener. This confirms the previous statement about blurring the perception of sound spaces (see subchapter 1.1).

In addition, chapter 2 explains that the level, frequency, type of sound signal, monaural and interaural group, and phase delays as well as sound reflections influence sound localization. In some cases these variables create sound spaces that are beyond the limits stipulated by the position of the sound sources, as is the case with the perception of diffuse sound fields in *Musical Situation 1* or the ambiguous sound spaces in *Polyphonic Continuum*.⁹⁷

As it can be seen in figures 15 and 16 above, both areas and circles have eight loudspeakers, which equal forty loudspeakers in total. As shown in figure 17, the 8-note groups can be radiated either by one sound source (sound-space density 8/1), one area

⁹⁷ Ambiguity of sound localization is particularly significant using the WFS, especially when the listener is positioned between the loudspeakers and the virtual position of the sound signal. In these cases the position of the sound event is completely unpredictable and uncertain.

(8/8), or one circle (8/8).



Figure 17. Sound expansion through different sound extensions using one sound source, one area or one circle.

Consequently, the same 8-note group can create three different sound spaces, which are determined by a specific sound location, sound-space density, and spatial extension of the notes in the 8-note groups, all of them participating at the same time in the perception of sound attribute, rhythm and texture variations (see chapters 2 and 3).

In *Musical Situation 1* the forty-two independent sound signals are spread in space using six circles, each one comprising eight sound sources (see figure 18).

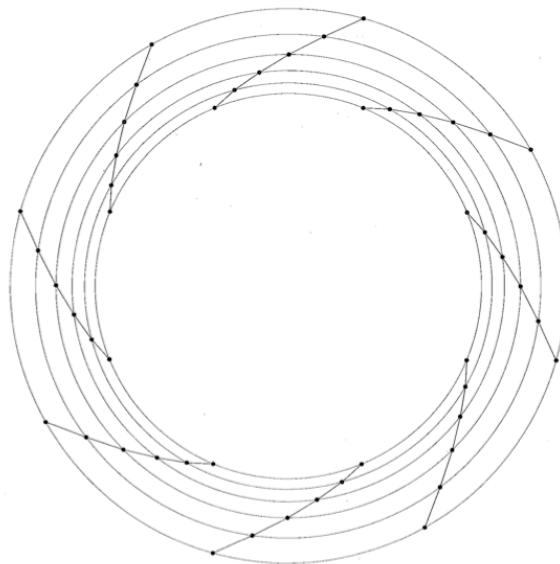


Figure 18. Sound space for the composition *Musical Situation 1*.

This spatial arrangement permits five sustained tones to sound simultaneously, to cover the whole area around the listener without placing any sound source in front of any other, and to create spatial depth by gradually increasing the distance of the circles in relation to the center.⁹⁸

In *Musical Situation 1*, the sound space is not divided into areas as occurred with *Topos* or *Polyphonic Continuum*, and the 8-note groups are always radiated using the eight sound sources corresponding to each circle. The intention is to create a homogeneous sound space, with no empty spaces, or vortex. However, amplitude variations are also applied to each layer, so the levels in relation to the listener are always different. These amplitude variations imply, on one hand, that each layer is perceived with important pitch, loudness, and tone color variations, and on the other, permit different tone gradations of the same sound spaces, which imply the perception of different gradations of diffuse sound fields mentioned above.

All the compositions can be played as well using eight sound sources. In this case, the sound sources are spread in space following the approximate shape of a regular octagon around the audience, as in figure 19.

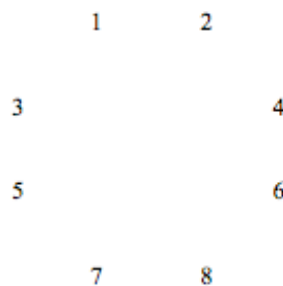


Figure 19. Spatial organization of the eight sound sources used for the experiments and compositions included in this thesis.

Using eight sound sources implies that the spatial extension for the areas is reduced to two sound sources only (sound-space density 8/2), and the previous five or six circles

⁹⁸ Besides the sound sources used for the circles (forty in total), two independent sound sources are normally placed in the middle of the audience, although they are not indicated in the figure because they are not always used and because they use always different positions, as shown in figure 87, pp. 194-195.

are reduced to a single circle. In this case, even though the result is satisfying enough, it presents two inconveniences. On one hand, the principle of no overlapping is not fulfilled as the four independent circles are reduced to one, which has important consequences regarding the perception of sound clarity and transparency. On the other hand, the number of sound sources in each area is reduced to two, and thus sound-space density variations are limited to 8/1 and 8/2, which dramatically reduces the perception of sound attribute and texture variations.

This thesis includes three versions of *Topos*, *Polyphonic Continuum*, and *Musical Situation 1*, one using eight sound sources, another using up to forty-two sound sources, and another using the WFS, which permits the virtual location of forty-two independent sound signals in any position in space as well as continuous movement from one sound source to another. These compositions are explained in detail in chapter 5.

In relation to the use of sound synthesis to create sound spaces, the compositions included in this thesis use no reverb or delay, nor any type of filter to create the illusion of spectral or Doppler shift variations associated with the movement of sounds in space. As already mentioned, the only parameters used to create different sound spaces and sound attribute and texture variations are the use of multiple sound sources together with amplitude variations.

This is one of the main characteristics of the compositions presented in this thesis, as they intend to create long and dynamic musical discourses using the movement of pure tones in space through different sound locations and sound-space densities.

1.8 Using Sound Spatialization to Produce Variations in the Perception of Sound Attributes.

Examples in the instrumental and electronic music literature where sound spatialization is used to produce variations in the perception of sound attributes, as it is proposed in this thesis, are rare. One of the few examples is found, again, in the music of Karlheinz Stockhausen, more precisely in his 8-channel composition *Cosmic Pulses*. This composition uses the rotation of sound around the audience at different speeds, which produces variations in the perception of pitch and timbre, as well as the perception of

specific sound fields.

Joachim Haas and Gregorio Garcia Karman carried out the technical realization of this work at the Experimental Studio in Freiburg between December 2006 and April 2007. Karman describes the perceptual effect of the OKTEG (Oktophonic Effect Generator) system, which was developed to achieve high-speed rotational effects, as follows:

Like in the Rotationsmühle –a device used in the spherical auditorium at the World's Fair in Osaka and later implemented as an output stage of the *Klangwandler* - the OKTEG provides the performer with manual control of rotation velocity, and different routings are accomplished by means of matrix programs. The *Rotationstisch*, first used as a spatialization instrument in *Kontakte*, was later further developed for exploring the artifacts, which appeared at very high rotation speeds. Following this idea, the OKTEG provides sample accurate trajectories and arbitrary high rotation speeds, assisting the exploration of a continuum linking space and timbre. When sound trajectories get close to the upper velocity range of 16 rot/sec in the composition of *Cosmic Pulses*, the perception of movement is gradually transformed into a diffuse and vibrating spatial quality. Higher rotation frequencies manifest themselves as audible modulation effects.⁹⁹

Certainly, the rotating loudspeaker designed by Stockhausen for the piece *Kontakte* to generate dynamic spatial trajectories and rotation effects implied pitch variations produced by the Doppler effect, as well as timbre variations produced by time-varying filtering, phase shifts, and other distortions which are difficult to be accurately reproduced electronically.¹⁰⁰

The relation between sound distance and the perception of pitch, loudness, and timbre was observed by Charles Ives, who, besides using sound spatialization to achieve sound clarity and transparency when different ensembles are playing simultaneously with different tonalities and tempi, considers as well the possibility of using different distances of the instruments to achieve the perception of musical perspective. As Ives says,

⁹⁹ Karman, Gregorio Garcia, in: *Stockhausen Edition n. 91 (Cosmic Pulses)*, Sonoloco Record Reviews, <http://home.swipnet.se/sonoloco25/stockhausen/91.html>, (accessed October 23, 2013).

¹⁰⁰ The possibility to electronically recreate the Doppler effect of moving sources was first undertaken by J. Chowning in 1968, who invented a computer processing system that allowed him to control the Doppler shift in frequency as a function of the radial velocity. This Doppler shift was used for the first time in his composition *Turenas* (1972). (Chowning, J., 2011, *Turenas: the realization of a dream*, article presented at the Journées d'Informatique Musicale Université de Saint-Etienne, Chowning, J., 1971, *The Simulation of Moving Sound Sources*, J. Audio Eng. Soc. 19, p. 2-6, and Roads, C., 1996, *The Computer Music Tutorial*, MIT Press, pp. 470-472).

As the distant hills, in a landscape, row upon row, grow gradually into the horizon, so there may be something corresponding to this in the presentation of music. Music seems too often all foreground even if played by a master of dynamics... It is difficult to reproduce the sounds and feeling that distance gives to sound wholly by reducing or increasing the number of instruments or by varying their intensities. A brass band playing pianissimo across the street is a different sounding thing than the same band playing the same piece forte, a block or so away. Experiments, even on a limited scale, as when a conductor separates a chorus from the orchestra or places a choir off the stage or in a remote part of the hall, seem to indicate that there are possibilities in this matter that may benefit the presentation of music, not only from the standpoint of clarifying the harmonic, rhythmic, thematic material, etc., but of bringing the inner content to a deeper realization.¹⁰¹

Creating such musical perspective and spatial depth requires that each layer is perceived coming from a different location and distance in relation to the others. Ives was conscious that using only dynamic variations is difficult to achieve such perspective in music.

As it is explained in detail in subchapter 2.4.1, the perception of both distance and amplitude variations have similar effects on the perception of loudness and tone color as soon as the sound is radiated 15m from the listener. Beyond this distance, particular sound attribute variations occur which depend on the characteristics of the environment. On one hand, the environment determines the delay time and amount reflections and reverberation. On the other hand, the length of the air paths to the ear drum determine the quantity of sound absorption, the pressure level of the direct sound, and the early and late reflections. These variations are not possible to achieve using amplitude variations only.

Musical depth is even more difficult to achieve when using synthetic sounds. Indeed, the perception of sound distance using amplitude variations is accurate only when sounds are already familiar to the listener. When using unfamiliar sounds, as is usual with synthetic sounds, amplitude variations give only an approximate perception of variations in distance.¹⁰² Stockhausen points out the difficulty of perceiving a precise distance using synthesized sounds, and concludes that distance is a secondary musical parameter, as it is determined by the timbre and loudness of the auditory event. Consequently, he considers

¹⁰¹ Johnson, M. E., 2002, *Charles Ives's (Utopian, Pragmatist, Nostalgic, Progressive, Romantic, Modernist)*, Yankee Realism, American Music, Vol. 20(2), University of Illinois Press, pp. 188-233.

¹⁰² Mershon, D. H. and King, L. E., 1975, *Intensity and reverberation as factors in the auditory perception of*

sound direction the principal spatial parameter, which, in addition, can be precisely determined using the serial method at the same level as timbre, amplitude, and rhythm.

The idea of musical perspective proposed by Ives is fully achieved when using large extensions of space. This approach is the essence of soundscape music, introduced by R. Murray Schafer, Barry Truax, and Hildegard Westerkamp among others. This musical aesthetic consists in the creation of musical structures based on field recordings, recreate the environmental sounds that occur in particular landscapes.¹⁰³ Each recorded sound has an implicit sound space determined by the characteristics of the environment, i.e. amplitude, levels of reverberation, and distance, which create the spatial depth or musical perspective proposed by Ives. This information can be accurately transmitted thanks to the new technological improvements in relation to sound recording and reproduction, especially since the development of digital sound recording.

At the same time, some composers directly employ large extensions of space to achieve the musical perspective proposed by Ives. This is the case, for instance, of Llorenç Barber (1948), who composes for the extension of entire villages and cities using the bells of the churches. Another example is the piece *Bran(d)t aan de Amstel* by the American composer Henry Brant (1913-2008), performed at the Holland Festival in 1994. This piece uses an endless number of musicians situated in numerous squares of Amsterdam, together with a youth jazz band, two choruses, two brass bands, four street organs, and four boats loaded with performers moving through the city canals.¹⁰⁴

Another way to use sound spatialization to perceive sound attribute variations is the one proposed in this thesis. Here our aim is to propose a way to perceive one sound with pitch, loudness, and tone color variations depending on the angle of incidence of a sound signal in relation to the external ear. This is possible due to the psychophysics involved in spatial hearing. The following chapters will explain in detail where, why, and how these variations on the perception of sound attributes occur, and at the same time how these variations can be successfully used in musical composition to create a satisfying musical discourse.

egocentric distance, Perception & Psychophysics, Vol. 18, pp. 409-415.

¹⁰³ Schafer, Robert Murray, 1977, *The Tuning of the World*, Random House, New York.

¹⁰⁴ Harley, M. A., 1997, *An American in Space: Henry Brant's "Spatial Music"*, American Music, Vol. 15(1), pp. 70-92.

2. SPATIAL HEARING AND SOUND PERCEPTION

Information about the transfer function of the external ear and its dependence on the direction and distance of the sound source is of interest not only in the study of spatial hearing, but also in other fields, for example, in examining how loudness and annoyance of noise depend on the position of the sound source.

Jens Blauert

To realize the aims of this thesis it was indispensable to undertake experiments, which would investigate to what extent sound attributes were affected by sound spatialization, and how they could be emphasized to become part of a musical discourse. Experiment 1 shows that sound is perceived with pitch, loudness, and tone color variations when radiated by eight loudspeakers situated at a certain distance from the listener in the approximate shape of a regular octagon (see figure 19, p. 69). To understand why these phenomena occur, it is necessary to explain in detail the processes involved in spatial hearing and their influence on sound perception. This chapter presents a theoretical explanation of the acoustic phenomena that occurred during the experiments, which investigate how sound spatialization produces variations in sound perception.

2.1 Sound Signal, Sound Event, and Auditory Event

To understand the influence of spatial hearing on sound perception, it is necessary to distinguish between three phases of sound: the sound signal, the sound event, and the auditory event.

Sound signal refers to the sound radiated by the sound source. In order to perceive the sound attribute variations that occur together with sound localization, it is necessary that the sound signals radiated by the loudspeakers are identical. Therefore, experiment 1 uses sine waves and other time invariant sound signals, which also limit the variations in loudspeaker response as much as possible.

The sound event refers to “the physical aspect of the phenomena of hearing,”¹⁰⁵ and consists of one or more sound signals radiated into space by one or more sound sources (or reflections) propagated as sound waves through the medium around the sound sources (normally air) until they reach the ear drums.¹⁰⁶ Therefore, obstacles in and the acoustic characteristics of the environment influence sound events.

Finally, the auditory event refers to the input signal at the ear drum, or, “what is perceived aurally.”¹⁰⁷ Assuming that the sound signals radiated by the loudspeakers are identical,¹⁰⁸ there are three possible reasons that can explain why they are perceived with pitch, loudness, and tone color variations when radiated from different positions in space:

- 1) the sound signals undergo different path-lengths to the ear drum and are influenced differently by the obstacles and reflections produced by the room, so the auditory system receives eight sound signals with time and level differences,
- 2) the auditory system filters each sound event differently depending on the angle of incidence to the ears, so they are perceived as different auditory events, or
- 3) both possibilities occur at the same time.

Studies on spatial hearing show that sound signals are distorted both by the acoustic characteristics of the environment as well as the auditory system itself. The following chapters explain the importance of each one of them on the perception of sound attribute variations related to sound localization.

¹⁰⁵ DIN 1320, 1959, *Allgemeine Benennungen in der Akustik* [Common terms used in acoustics], Beuth-Vertrieb, Berlin.

¹⁰⁶ cf. Blauert, 1997, p. 22.

¹⁰⁷ Ibid, p. 2.

¹⁰⁸ The possibility that the perception of sound attribute variations is also due to different responses of the loudspeakers is dismissed because the eight loudspeakers used for the experiments were identical. If variations occur, they should be studied as an independent element influencing the perception of sound attributes, which cannot be considered in the scope of this thesis.

2.2 The Influence of the Auditory System¹⁰⁹ on the Perception of Sound Attribute Variations

Studies on sound localization prove that the transfer functions $\underline{A}(f)$ that occur at the pinna (5), ear canal (6) and ear drum (7) (see figure 20), as well as the head, imply pressure level, phase delay, and group delay variations that depend on the angle of incidence of the sound events at the external ear.

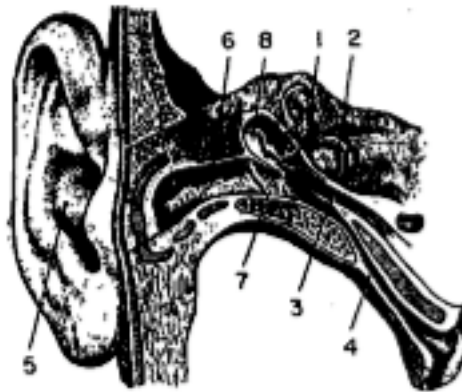


Figure 20. Cross section of the ear.

This is important for this research, as it proves that the perception of sound attributes is ultimately defined by the auditory system. The following sections present each part of the external ear separately, so it can be explained in detail how they influence the perception of sound events.

¹⁰⁹ The auditory system consists of the external ear (*auris externa*), the middle ear (*auris media*) and the inner ear (*auris interna*). The external ear includes the pinna (or *auricula*) (5) and the external ear canal (*meatus acusticus externus*) (6). The ear drum (*membrana tympani*) (7), the tympanic cavity (*cavum tympani*), and the ossicles within the cavity known as hammer, anvil and stirrup constitute the middle ear. The inner ear includes, among other organs, the organ of Corti, which lies within the Cochlea (2), and contains the receptors for the sense of hearing. The cross section of the ear presented in figure 2 is adapted from Möricke and Mergenthaler, 1959, *Biologie des Menschen*, Quelle and Meyer, Heidelberg.

2.2.1 The Importance of the Pinna¹¹⁰ and the Head

The pinna and the head are by far the most important organs in transforming the sound attributes of the sound events. Several tests show that the pinna functions as a linear filter whose transfer function depends on the direction and distance of the sound source. Blauert states, “The pinna codes spatial attributes of the sound field into temporal and spectral attributes (...) by distorting incident sound signals linearly and differently depending on their position.”¹¹¹

Reflection, shadowing, dispersion, diffraction, interference, and resonance are some of the physical phenomena that occur when sound reaches the pinna, and all of them have important consequences in relation to sound perception.

Batteau presented the first description of the pinna as a sound reflector, and suggested that, “the dependence of the transfer function of the pinna on distance and direction of the sound source is due to differences in the path lengths between the direct and reflected sound”.

Further studies undertaken by Shaw and Teranishi¹¹² demonstrate that instead of reflection and shadowing, diffraction and dispersion processes occur if the reflecting surface of the pinna is small in comparison to the wavelengths. Dispersion can produce an indefinite number of delays, which have as well an important role in sound perception. In addition, the pinna has cavities in which a “guided” propagation of sound waves takes place. Studies undertaken by Shaw and Teranishi demonstrate that resonance can take place in those cavities when their width is as small as a quarter-wavelength.

The disturbance of the sound field by the head also has a significant influence on the sound signals reaching the pinna, as the head influences sound events through diffraction, which has a direct influence on sound pressure. To what extent diffraction affects sound pressure at the ear drum depends on the sound incidence angle, as shown in the figures 21 and 22 below.

¹¹⁰ The pinna represents the most visible part of the external ear, and consists of a framework of cartilage covered with skin surrounding the entrance to the ear canal. It presents high impedance compared with that of air (cf. Blauert, 1997, p. 53).

¹¹¹ Blauert, 1997, p. 63.

¹¹² Shaw, E. A. G., and R. Teranishi, 1968, in: *Sound pressure generated in an external-ear replica and real human ears by a nearby sound source*, J. Acoust. Soc. Amer. 44, pp. 240-249.

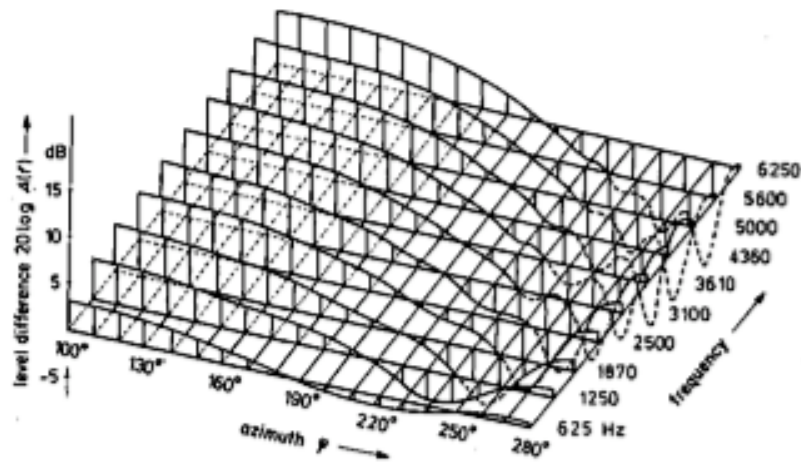


Figure 21. Sound pressure as a function of sound incidence angle at the left-ear point compared to sound pressure with the sphere removed.

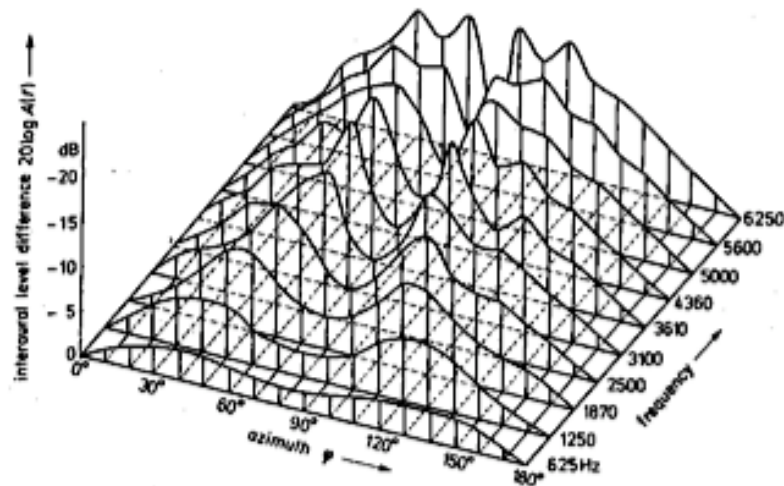


Figure 22. Interaural difference in sound pressure level as a function of sound incidence angle, calculated for a sphere of 17.5 cm in diameter with the ears represented by points on its surface at the positions $\varphi = 100^\circ$, $\varphi = 260^\circ$ and $\delta = 0^\circ$.

As these figures demonstrate, the differences of sound pressure level, interaural sound pressure, interaural phase, and interaural group delays produced by sound diffraction

are functions of sound incidence angles.¹¹³ In addition, diffraction produced by the head has different consequences depending on the frequency.

Figure 21 shows the differences of sound pressure level of an undisturbed plane wave at the position of the left ear of a model sphere compared to sound pressure with the sphere removed, for sound incidence angles in the range of $100^\circ \leq \varphi \leq 280^\circ$ in the horizontal plane.¹¹⁴ Observing the resulting values, it is noticed that sound pressure at some frequencies can be higher when the head is positioned directly between the ear and the sound source (280°) compared to a free sound field. In this case, the head has an amplifying rather than an attenuating effect, which is a well-known phenomenon in diffraction.¹¹⁵

Figure 22 shows the interaural difference in sound pressure level as function of the sound incidence angle. Notice that at angles of 0° and 180° the interaural level difference is of 0 dB, coinciding with the position of the sound source at the median plane, where the distance at the two ears is the same.

Attending to the results of these tests, it can be deduced that sound pressure at the ear drum depends strongly on the transfer functions occurring at the pinna and the head. Their influence must be considered to measure the transfer functions of the external ear precisely.

¹¹³ cf. Blauert, 1997, pp. 70-74.

¹¹⁴ All references to the position of both sound events and auditory events included in this chapter are based on the head-related system of spherical coordinates as shown in figure 23:

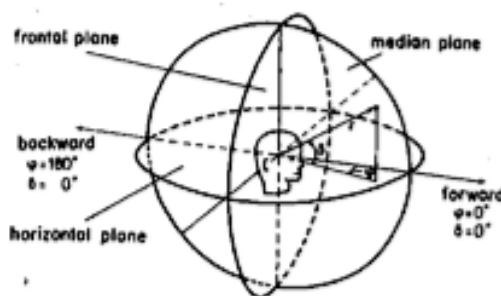


Figure 23. Head related system of spherical coordinates.

In figure 19, the space is divided into three planes: the horizontal plane, the median plane and the frontal plane. The position of the sound sources is determined by the angles φ (horizontal plane) and δ (median plane), and the distance (radius) of the sound source in relation to the center of the head, which is located halfway between the entrances to the two ear canals. The tests in this thesis and the compositions use the horizontal plane only, although it may not coincide with the horizontal axis of the two ears as shown in figure 1.

¹¹⁵ Ibid., p. 71.

Figures 24 and 25 below show that the interaural phase delay and interaural group delay are functions of frequency and sound incidence angle. Notice that in both cases the maximum values correspond to an incidence angle of 90° , where the sound is weaker and reaches the far ear later.

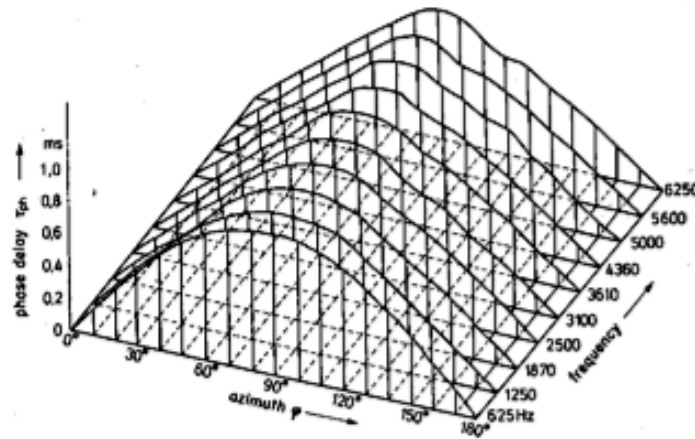


Figure 24. Interaural phase delay.

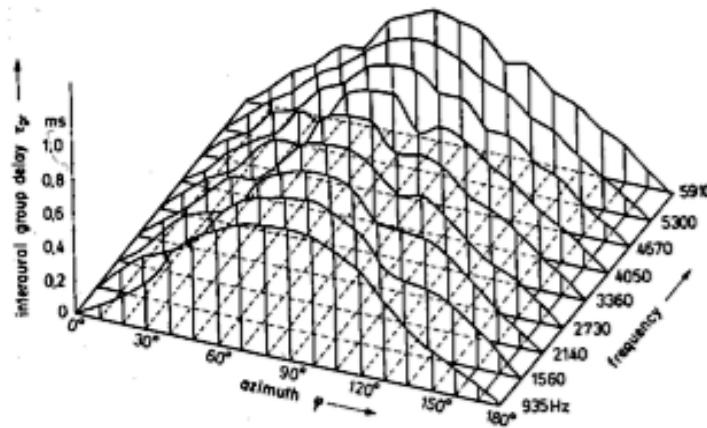


Figure 25. Interaural group delay.

In order to perceive pressure level, phase and group delay variations of one sound produced when sound reaches the external ear from different angles, and to incorporate them into a musical discourse, this thesis proposes to divide a sine wave in multiple small sound units and radiate them through multiple loudspeakers.

For both the experiments and compositions the loudspeakers are arranged as shown in figure 19 (p. 70). However, according to the results shown in the previous figures, it may have been more effective to arrange the eight loudspeakers so four of the vertices of the octagonal shape coincide with angles of 0° , 90° , 180° , and 240° and not as the arrangement used (see figure 26). In doing so, the variations in pressure level, and phase and group delays produced by other sound signals coming from other angles of incidence to the ear would have been emphasized.

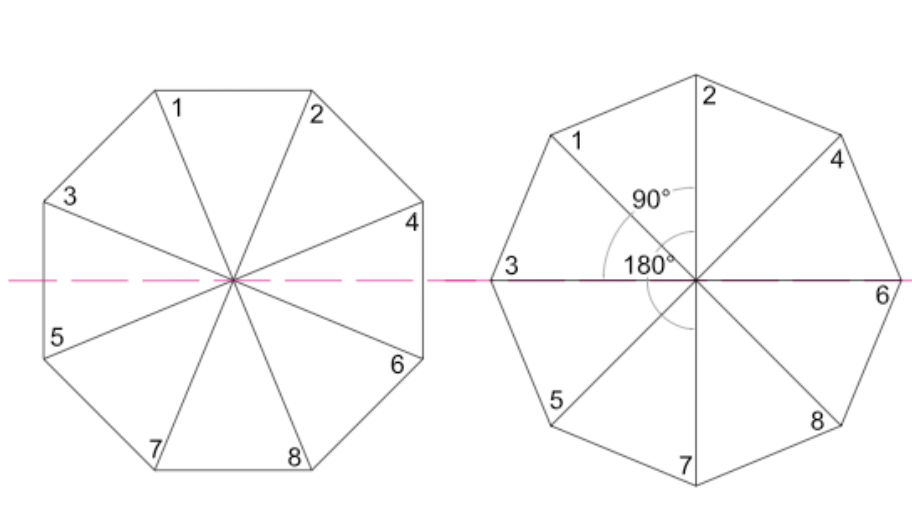


Figure 26. Graph comparing two spatial arrangements of the loudspeakers: the one used for the experiments (left), and the one recommended (right).

This arrangement was not chosen because the experiments and compositions were created respecting the original position of the loudspeakers at CIME, which proved to be adequate for the purposes of the research. Furthermore, the experiments presented in the previous figures reflect the results of scientific research in which the sound sources are positioned at exact angles in relation to the axis of the two ears in an anechoic chamber. To perceive similar results implies that the listener should be placed at the exact center of the octagon with the head immobilized, so the exact incidence angles of the sound signals to the ears are achieved. However, this thesis is primarily interested in the perception of sound attribute variations involved in sound localization that occur in normal performance conditions, which implies that the position of the loudspeakers and listeners is not fixed and strictly calculated. As shown in the experiments undertaken here, as soon the

loudspeakers are situated at a certain distance around the listener, he or she experiences sound attribute variations, and the angles in relation to the listener are of secondary importance.

2.2.2 The Secondary Role of the Ear Canal¹¹⁶ and Ear Drum¹¹⁷

The ear canal is the least important organ of the external ear in the distortion of sound signals, as no significant transfer functions occur. As Metz point out, “(in the ear canal) the acoustic impedance of skin over bone is approximately the same as that of the surface of water. [...] It follows that the coefficient of reflection of the walls of the ear canal is nearly unity.”¹¹⁸

In addition, there are no pronounced propagation losses in the ear canal, as might be expected because of the hair inside.¹¹⁹

In relation to the ear drum, recent studies indicate that the dependence of the transfer functions on the direction and distance of the sound source, which contain “the spatial characteristic” of the auditory event, is unaffected by ear drum impedance in the normal spectral band of hearing range.

The unimportant role of the ear canal and the ear drum is somehow logical, as the ear drum must reproduce as accurately as possible the transfer functions occurring at the pinna, so the information on sound localization is well-transmitted to the middle and inner ears. The angles of incidence of the sound events are coded at the pinna, and the sound attributes are altered according to the transfer functions occurring there.

¹¹⁶ The ear canal is a slightly curved tube that connects the pinna with the ear drum. Sound travels through the ear canal and ends up at the ear drum in the form of sound pressure.

¹¹⁷ The ear drum is a nearly circular, or slightly elliptical, thin, cutaneous diaphragm. Motions of the ear drum occur when there are air pressure changes in the ear canal. Sound pressure at the end of the ear canal causes the ear drum to oscillate. Thus, the ear drum functions as a “pressure-sensitive receiver”, which means that the diaphragm receives the sound pressure oscillation force on one side only.

¹¹⁸ Metz, O., 1946, *The acoustic impedance measured in normal and pathological ears*, Acta Oto-laryngol. Suppl. 63.

¹¹⁹ Blauert, 1997, p. 56.

2.3 What alterations do sound signals undergo on their path to the ear drum, and how do they depend on the direction and distance of sound sources?

As the external ear is a linear system, the linear distortions that a sound signal undergoes at the external ear can be measured according to the system's transfer functions,¹²⁰ as shown in figures 27 and 28.

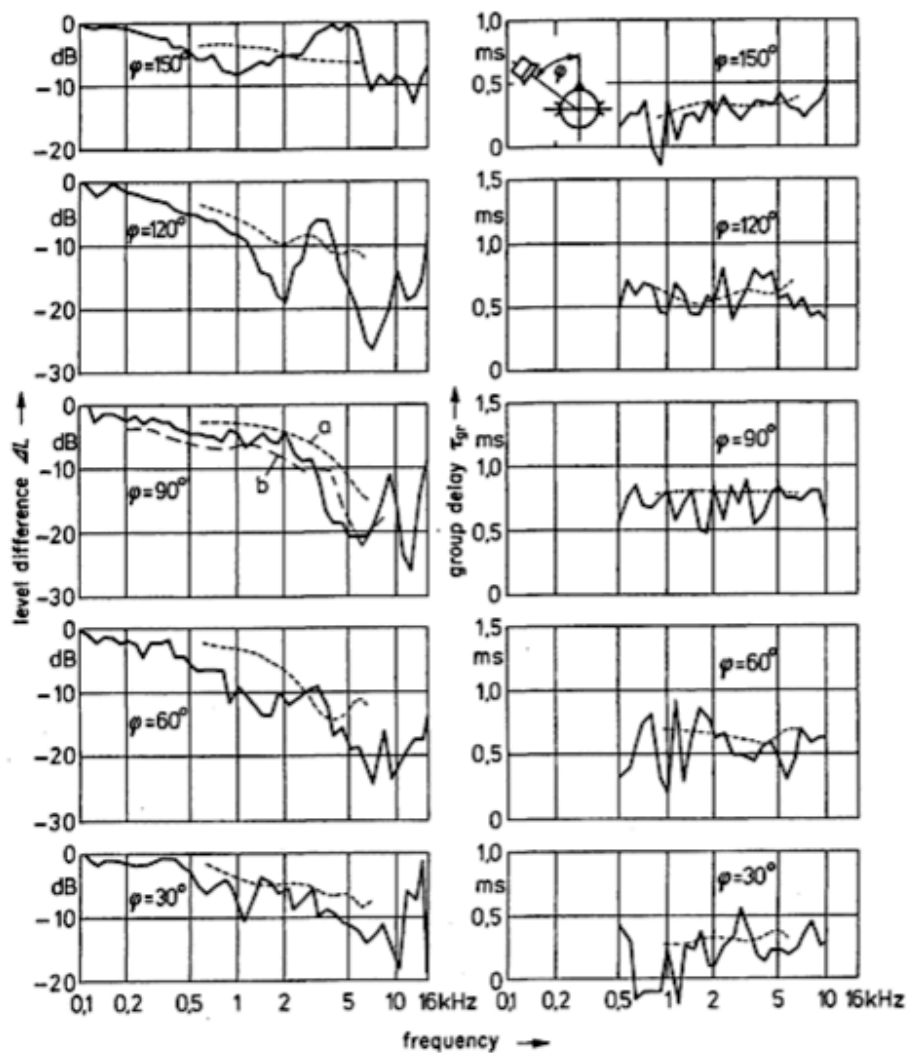


Figure 27. Interaural transfer functions for several directions of sound incidence in the horizontal plane.

¹²⁰ The transfer functions occurring at the external ear are defined as the complex ratio of the Fourier spectrum of the output variable to that of the input variable (Blauert, 1997, p.78).

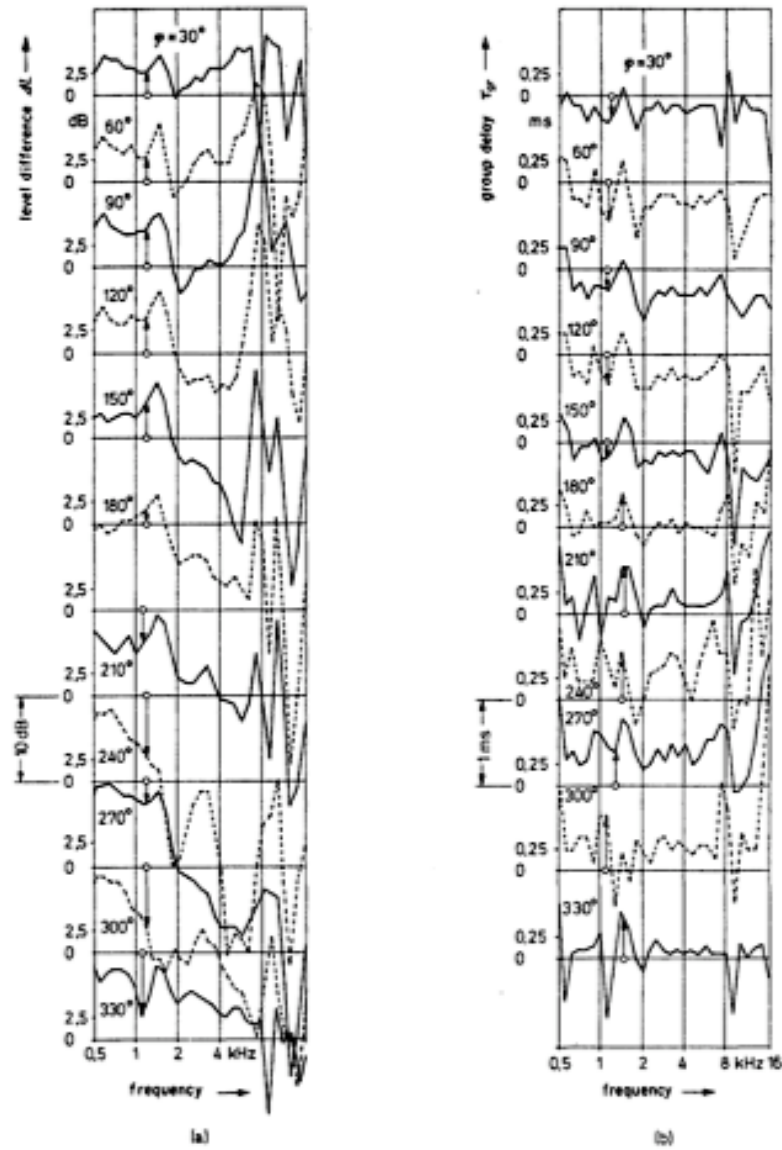


Figure 28. Monaural transfer functions of the left ear for several directions in the horizontal plane, relative to the sound incidence from the front, $\varphi = 0^\circ$ and $\delta = 0^\circ$.

Figure 27 shows the dependence of the interaural transfer functions¹²¹ on both the angle of incidence and frequency, for sound sources situated at a distance of 3 m at

¹²¹ The interaural transfer function compares sound pressure at corresponding points in the two ear canals with the sound pressure at the ear facing the sound source (Blauert, 1997, p. 78).

different angles in the horizontal plane in an anechoic chamber. The angles are indicated inside each graph. Figure 28 shows the monaural transfer functions¹²² of the left ear for several directions in the horizontal plane in relation to the values of sound incidence from the front ($\varphi = 0^\circ$ and $\delta = 0^\circ$) in an anechoic chamber where the sound sources are situated at a distance of 2m.¹²³

These figures show that both monaural and interaural transfer functions affect the pressure level and phase delay of the sound events differently, depending on the frequency, distance, and direction of the sound source. The monaural transfer functions affect the time and level differences of the individual spectral components of the each individual ear input signal differently. The interaural transfer functions affect the time and level differences between the corresponding spectral components of the same sound signal at the two ears.¹²⁴

The fact that the transfer functions are frequency dependent $\underline{A}(f)$ means that the resulting auditory events are different depending on the frequency of the sound signal. Indeed, during the experiments it was noticed that the perception of sound attribute variations was more important with low frequencies than with high frequencies. With frequencies around 2000 Hz, sound attribute variations were barely perceptible or nonexistent. As it can be seen, both sound pressure level and group delay differences are less important around 2000 Hz compared to the lower frequencies.

Even though lower frequencies (less than 1 kHz), tend to be less affected by monaural and interaural transfer functions occurring at the external ear, they are used often in the compositions. On one hand, the timbre of lower frequencies is rich and musically interesting. In addition, this range is common to instrumental music, and higher frequencies are used much less. On the other hand composing with higher frequencies is impractical, as they are barely audible when combined with other lower frequencies, particularly when using sine waves, square waves, and triangle waves. The highest frequency used in the compositions is 1224 Hz, which is used only once in the composition *Musical Situation 1* (09'00''-09'45'').

¹²² The monaural transfer function compares sound pressure at a point in the ear canal for different directions and distances of the sound source with the measurements of a sound source at a reference distance and angle (normally $\varphi = 0^\circ$ and $\delta = 0^\circ$) (Blauert, 1997, p. 78).

¹²³ Ibid., p. 90.

2.4 The Importance of Sound Pressure Level at the Ear Drum for the Perception of Loudness and Tone Color Variations

The first experiments undertaken in this thesis show that varying the amplitude of the same sound signal slightly produced effects on the perception of pitch, loudness, and tone color variations similar to those achieved by sound localization, proving that pressure level variations are an extremely important factor in determining the sound attributes of auditory events. Studies on spatial hearing demonstrate that the most important information used by the auditory system to determine sound localization is interaural sound pressure level variations at the ear drum.¹²⁵ Consequently, the perception of pitch, loudness, and tone color variations may also be produced, in addition to sound direction, either by different distances of the sound sources in relation to the listener, or by directly manipulating the amplitude of the sound signals.

2.4.1 The Influence of Distance on Level Pressure

In the experiments included in this thesis, the loudspeakers were placed at a distance of approximately 1,5m to the center. Therefore, the distance of each loudspeaker in relation to the listener is not strictly calculated, and varies for each loudspeaker.¹²⁶ As small differences in the angle of incidence to the ear have important consequences for the perception of pitch, loudness, and tone color variations, which are experienced when moving the head only slightly, small differences in distance may also have an important influence on the pressure level at the ear drum. Therefore, the perception of sound attribute variations between the notes in the 8-note groups may not only be due to differences in the angles of incidence to the ear but also due to different distances.

¹²⁴ Ibid., p. 177.

¹²⁵ Ibid., p. 63.

¹²⁶ The possibility to realize experiments using the exact same distance between the loudspeakers and the listener is not considered in this thesis. On one hand, such experiments would require precise distance measurements that are very difficult to acquire, and on the other hand, it is assumed that exact distances between loudspeakers are rarely found in normal performance conditions. In this sense, it must be underlined that the goal of this investigation is to apply the perception of sound attribute and texture variations related to sound location and sound-space density variations to musical composition using the conditions of any normal electroacoustic performance environment. This implies that the loudspeakers are placed at variable distances to the center of the room, sometimes influenced by the architectural singularities of each space. In addition, as already pointed out in subchapter 1.5, the listeners are situated in different places, so the distance between

Studies on sound localization show that the linear distortions introduced by the head and the external ear depend on not only the angle of incidence, but also on the distance of the sound source. This is especially true when the distance between the loudspeakers and the listener is not larger than 3m.¹²⁷ For instance, figure 29 shows the differences in level and group delay of the ear input signals at distances of 25cm and 3m, showing that at smaller distances the increase in pressure level becomes greater, so small distances are more effective to produce more changes in tone color.

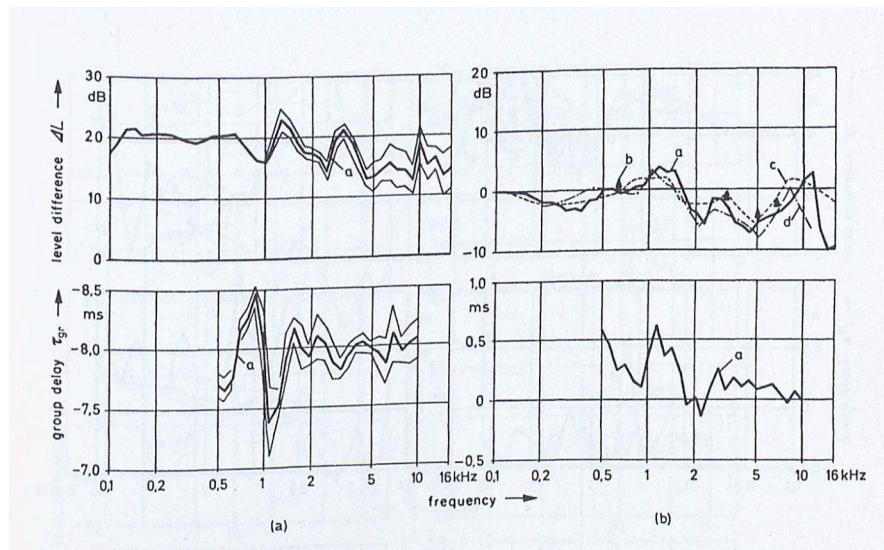


Figure 29. Differences in level and group delay of the ear input signals at distances of 25 cm. (a) ($\varphi = 0^\circ$ and $\delta = 0^\circ$), and 3 m. (b) ($\varphi = 180^\circ$ and $\delta = 0^\circ$).

Von Békésy¹²⁸ used the relation of the transfer functions at the external ear to explain distance hearing at short distances, and deduced that low-spectral components of a broadband signal show relative increase of sound velocity in the near field as compared to the far field. This assumption is supported by the observation that the tone color of the auditory event becomes darker as a sound source is brought closer to the subject.

the listeners and loudspeakers is different for each one of them.

¹²⁷ Other studies on stereophonic sound reproduction confirm that small changes in interaural level pressure at the ears result in large changes in the perceptual position of the sound sources, which implies that extending the distance of the loudspeakers beyond $\pm 45^\circ$ degrades the stereo image significantly (Theile, G., 1980, *On Localisation in the Superimposed Soundfield*, Doctoral Thesis, Berlin University of Technology).

¹²⁸ Von Békésy, G., 1938, *Über die Entstehung der Entfernungsempfindung beim Hören* [On the origin of the sensation of distance in hearing], Akust. Z. 3, pp. 21-31.

Increasing the level in the ear input signal represents a change in tone color of the auditory event without changing the shape of the spectrum.

Indeed, by approaching the sound source, or with the increase of sound pressure level at the ears, tone color becomes darker. The darkening of tone color is understood when examining the curves of equal loudness showed in Figure 30. As it can be seen, for sine waves with sound incidence from the front, the curves of equal loudness level indicate that the low-frequency components of a broadband signal acquire more perceptual weight (dB) in comparison with the high-frequencies components. As soon as a sound radiating a broadband signal is brought closer to the subject, the distance of the auditory event decreases, its loudness increases, and its tone color becomes darker¹²⁹.

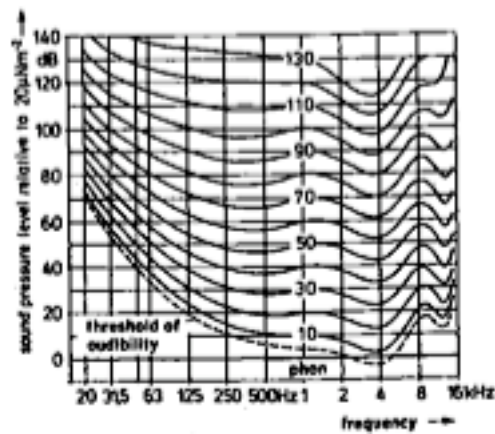


Figure 30. Curves of equal loudness for sine waves with sound incidence from the front.

Regarding the experiments and compositions presented in this thesis, the possibility to place each loudspeaker using more variable and pronounced distances within a radius of 3m to emphasize the differences in sound pressure level and tone color between the notes in the 8-note groups is not considered. The main reason is that in doing so, sound pressure differences may be too evident and differentiated, provoking the perception of undesired rhythmic patterns. These rhythmic patterns impede the listener to focus the attention on the perception of sound attribute variations, as they become masked to a great extent by the perception of rhythm.

Distances of the loudspeakers beyond 3m in relation to the listener have important consequences for the perception of pitch, loudness, and tone color variations. When the

¹²⁹ cf. Blauert, 1997, p. 121.

piece *Musical Situation 1* was performed in the concert hall at the Universidade de Aveiro and at the H-104 Saal at the TU in Berlin, the perception of sound attribute variations was not as clear and varied compared to the studio dimensions at CIME.¹³⁰ The reason is that sound pressure level changes are more evident at short distances, possibly because the sound events are not as strongly affected by early and late reflections, which create diffuse sound fields. As it is explained in chapter 2.7, at less than 15m the pressure level of the primary sound and its reflections determines the level of the sound signal at the ear drum, influencing the perception of pitch, loudness, and tone color variations.¹³¹

When sound is radiated at a distance of more than 15m, the air path also plays an important role in the distortion of the sound signal. Even though the pressure level of the sound signals at the ear drum depends on the angle of incidence, there is an additional attenuation that depends on the length of the air path. This attenuation varies depending on the shape of the spectrum, as the relative level and phase curves are functions of frequency. For instance, higher frequencies are more attenuated than lower frequencies as distance increases.¹³²

It would be interesting to perform the pieces presented here in open spaces to experience how large distances together with the decrease of reflections affect the perception of sound attribute variations in comparison to enclosed spaces. Unfortunately, this experience could be not realized before the presentation of this thesis.

2.4.2 Using Amplitude Variations to Produce the Perception of Loudness and Tone Color Variations

Variations on the amplitude of the sound signals can produce effects on the perception of loudness and tone color variations that are similar to those achieved by varying the distance of the sound signals in relation to the listener, as amplitude variations also modify the pressure level at the ear drum. This explains why amplitude variations can also be associated with changes in the distance of the sound signals (see subchapter 1.8). As Stockhausen points out: “Concerning distance, amplitude can be responsible for the spatial location of a sound, so that amplitude can be defined as a spatial quality of

¹³⁰ Centro de Investigação em Música Electrónica at the Universidade de Aveiro.

¹³¹ Ibid., p. 280.

sound.”¹³³

The advantages of using amplitude variations compared to distance variations is that they can be better controlled and manipulated. This is especially useful in electronic music, as the amplitude relations between sounds can be precisely determined.

The use of amplitude variations on the perception of loudness and tone color variations is especially relevant to *Musical Situation 1*. In this composition the use of very few sustained tones is possible thanks to the perception of sound attribute variations achieved through amplitude variations. Especially illustrative are the differences on loudness and tone color between exposition 1 (00’00’’ to 02’10) and exposition 2 (02’30’’ to 04’30’’). Even though the exact same five sustained tones are used, in exposition 1 they are always played *ff*, while in exposition 2 they are played *ppp*. Each exposition is perceived very differently due to the tone color variations resulting from such amplitude differences. Another characteristic of such amplitude variations is that they create highly differentiated sound spaces (see subchapter 1.7) and the perception of diffuse sound fields (see subchapter 2.8.3).

2.5 The Effects of Sound Localization on Pitch Perception

2.5.1 Hearing Pitch

Two different theories of pitch perception are used to explain how the auditory system is able to identify changes in the frequency domain: the “place” theory and the “temporal” theory.¹³⁴

The place theory relates pitch perception to the frequency analysis undertaken by the basilar membrane within the cochlea (n. 5 in figure 20, p. 76), where different components of the waveform fire the hair cells corresponding to specific areas of the membrane, allowing a higher center of neural processing and the brain to determine which frequency corresponds to the input signal.

¹³² Ibid., p. 118.

¹³³ Stockhausen, K., 1975 (a), p. 160.

¹³⁴ Howard, D., David, M., Agnus, J., 2001, *Acoustics and Psychoacoustics* (second edition), Music Technology Series, Focal Press, MA, p. 119-136.

The temporal theory of pitch perception relies on the timing of neural firings generated in the organ of Corti,¹³⁵ which occur in response to the vibrations of the basilar membrane. In this case, the perception of pitch is determined by the fundamental frequency that excites a specific place of the basilar membrane, which can be found in an analysis of the nerve firings occurring all across the basilar membrane (see figure 31).

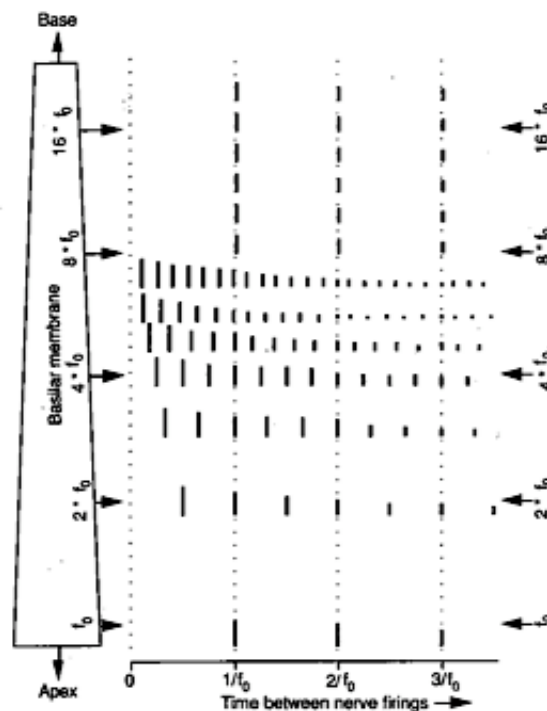


Figure 31. Possible nerve firings across the basilar membrane for the 16 first harmonics of the input signal.

Recent psychoacoustic research on pitch perception indicates that place and temporal theories function together. Moore (1982) presents the following model of pitch perception (see Figure 32):

¹³⁵ The organ of Corti lies within the cochlea (see figure 17, p. 71, n. 2), and contain the receptors of the sense of hearing.

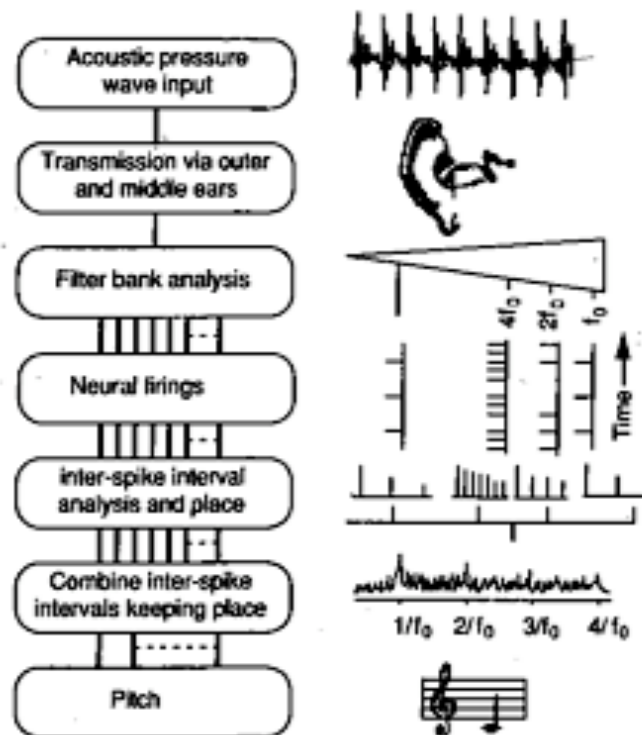


Figure 32. A model of pitch perception based on Moore (1982).

Moore describes figure 32 as follows:

The acoustic pressure wave is modified by the frequency response of the outer and middle ears (...) and analyzed by the place mechanism which is equivalent to a filter bank analysis. Neural firings occur stimulated by the detailed vibration of the membrane at places equivalent to frequency components of the input sound based on phase locking but not always once per cycle (...). The fact that firing is occurring from particular places provides the basis for the place theory of pitch perception. The intervals between the neural firings (spikes) are analyzed and the results are combined to allow common intervals to be found which will tend to be at the fundamental period and its multiples, but predominantly at $(1 / f_0)$.¹³⁶

¹³⁶ Howard *et al.*, 2001, pp.133-134.

2.5.2 Influence of Sound Intensity on Pitch Perception

Pitch perception is directly related to frequency, and this is the basis for both the place and temporal theories of pitch perception. However, changes in pitch also occur by modifying the intensity and duration of a sound while keeping its frequency constant. Sound intensity variations are the most important factor in determining the perception of microtonal pitch variations that occur when the same tone is radiated from different locations, such as in experiment 1.

Figure 33 shows that when varying the intensity between 40 dB SPL and 90 dB SPL while keeping the f_0 constant, a change in pitch is perceived for all f_0 values other than those around 2 kHz. For f_0 values greater than 2 kHz the pitch becomes sharper while increasing the sound intensity, and below 2 kHz the pitch becomes flatter as the intensity is increased. Rossini (1989) suggests a change of 17 cents (0.17 of a semitone) for an intensity change between 65 dB SPL and 95 dB SPL, although he doesn't specify which type of signals and under which conditions this value is deduced. He also points out that the effect of intensity changes on pitch perception is especially relevant when using sine waves, and less noticeable when using complex sounds. For this reason, this thesis employs sine waves and other time invariant sound signals to experience sound attribute variations involved in sound localization.

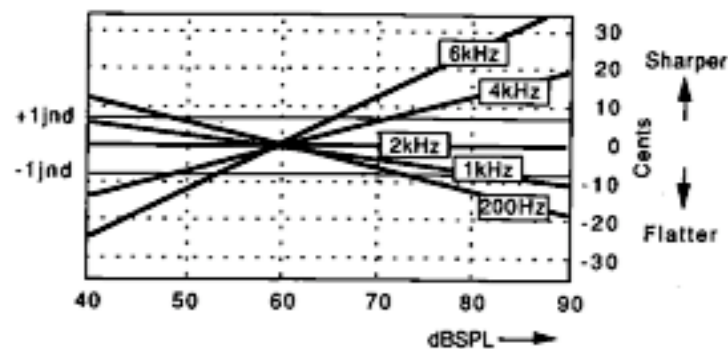


Figure 33. Pitch shifts perceived when the level of a sine wave with a constant fundamental frequency is varied (after Rossing, 1989).

Rossini suggests two circumstances where it is possible to perceive pitch variations associated with intensity variations:

- 1) when hearing the final loud organ chord in a high reverberant building, as pitch seems to rise as the sound decays (Parkin, 1974).
- 2) when hearing percussion instruments, as pitch shift is also observed for sounds with varying rates of waveform amplitude while f_0 remains constant.

This thesis incorporates spatial hearing as another possibility to perceive pitch variations, as it shows that sine waves or other time invariant sound signals with the exact same frequency are perceived with significant microtonal pitch variations when radiated successively from different sound locations, as shown in experiment 1.

2.5.3 Influence of Sound Duration on Pitch Perception

Sound duration may also influence the perception of pitch variation, as each frequency needs a minimum number of cycles to be clearly perceived. Figure 34, for instance, shows the number of cycles needed for different fundamental frequencies.

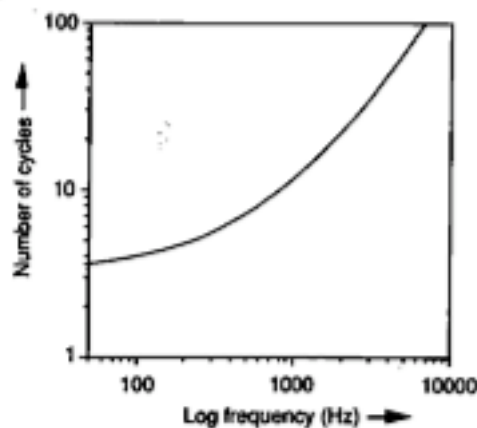


Figure 34. Effect of duration on pitch in terms of number per cycles needed for a distinct pitch to be perceived for a given fundamental frequency (from Rossing, 1989).

Even using short note durations, a given frequency may be perceived as being more pitched rather than non-pitched, although the perception of pitch is very diffuse and

listeners cannot make a precise judgment. This is exactly the case in *Musical Situation 1* (04'35'' to 06'35''), where the fragments of notes in the 8-note groups of the sustained tone are presented at regular temporal distances from one another and their note durations are increased one millisecond on every successive pulse, beginning with a note duration of 1ms (see figure 85, p. 191). During such note dilations, it is perceived that with very short durations the notes are already more pitched than not pitched, although it is not until the note has reached a certain duration that pitch is clearly recognizable.

In addition, while the note duration is increased, the note is perceived as progressively lower. This may be attributable to the increase of the sound intensity produced by the reflections of the room. As shown in figure 33 (p. 93), frequencies below 2 kHz may be perceived as lower as their intensity increases. Thus the frequency of the tone used in *Musical Situation 1* is 408 Hz.

2.6 Head Movement in Relation to the Perception of Sound Attribute Variations

As the transfer functions of the external ear depend on the position of the sound source in relation to the subject's head (see subchapter 2.2.1), head movement may also have an important role in the perception of sound attribute variations.

During the tests undertaken in this thesis, it was noticed that the perception of sound attributes varied by moving the head. Indeed, keeping the head immobile, sounds are perceived with the same sound attributes, which change when the head is moved. Even slight head movements have important consequences for the perception of the sound attributes.

Stockhausen points out as well the effects of head movement on the perception of sound attributes. In relation to his piece *Sirius*, which used, same as the compositions presented in this thesis, eight sound sources, Stockhausen states,

Sirius is based entirely on a new concept of spatial movement. The sound moves so fast in rotations and slopes and all sorts of spatial movements that it seems to stand still, but it vibrates. It is [an] entirely different kind of sound experience, because you are no longer aware of speakers, of sources of sound – the sound is everywhere, it is within you. When you move your head even the slightest bit, it changes color, because different distances

occur between the sound sources.¹³⁷

The effects of head movement on sound perception could be especially important in those cases where sound remains static. Through head movement, sound could be perceived with gradual sound attribute changes. Indeed, the only difference between moving sounds discontinuously, as used in the experiments and compositions presented here, and moving the head, is the possibility to perceive gradual and “continuous” change of the sound attributes. The same gradual effect could be achieved by moving sound continuously through space.¹³⁸

For the purposes of this thesis it is not necessary to consider head movement as an independent case, as both sound movement and head movement have similar consequences on the perception of sound attribute variations. The goal of this thesis, which is to explore the possibilities of spatial hearing in relation to sound perception, is fully achieved by the discontinuous movement of sound in space. In addition, sound movement permits rapid change of the position of the sound, and the use of any sound location 360° around the listener. Both the rate of change and the spatial extension in this case are not possible to achieve by moving the head.¹³⁹

2.7 Using Multiple Sound Sources and Sound Reflections to Create Diffuse Sound Fields

The perception of diffuse sound fields occurs when it is not possible to locate the position of the sound sources because they are masked by the reflections. Sound reflections occur in any non-free sound field,¹⁴⁰ and the amount and level of reflections depend on the

¹³⁷ Felder, D., 1977, *An interview with Karlheinz Stockhausen*, Perspectives of New Music, Vol. 16(1), pp. 85–101.

¹³⁸ It would be interesting to compare effects of head movement on the perception of sound attributes with the real or virtual movement of the sound source with the WFS. In this way, we could study the accuracy of virtual sound production in relation to sound movement offered by this system.

¹³⁹ To incorporate head movement as a parameter in musical composition could be the subject of a further research on spatial hearing in relation to musical composition. However, such research goes beyond the scope of this thesis.

¹⁴⁰ A non-free sound field is created by the superposition of the original sound source and the “virtual” sound sources or reflections radiated by larger planar surfaces in comparison to the wavelength of the propagating sound: “Any disturbed sound field can be considered an undisturbed (free) sound field generated by multiple sound sources (in extreme cases an infinite number of sound sources)” (Blauert, 1997, p. 201). Although the transfer functions at the external ear occurring in free sound fields are also applicable, other parameters must

dimensions, obstacles and acoustic characteristics of the space. Normally, diffuse sound fields are perceived in large reverberant halls.

However, this thesis shows that diffuse sound fields can be achieved independently of the dimensions and acoustic characteristics of the room. In *Musical Situation 1*, for instance, the use of continuous sustained tones formed by the sum of small sound units, i.e. notes in the 8-note groups, radiated in space through multiple loudspeakers spread around the listener, permit the creation of exceptional diffuse sound fields in small rooms with a few reflections such as the electronic studio at the Universidade de Aveiro (CIME).

Figure 35 shows how diffuse sound fields depend on both the level of correlation between the sound signals generated by multiple sound sources and the level of the primary sounds in relation to the reflections. These exceptional sound fields may result from the superposition of the multiple primary sounds radiated by the loudspeakers, the early reflections and late reflections, and the amount of uncorrelated sound signals they generate.

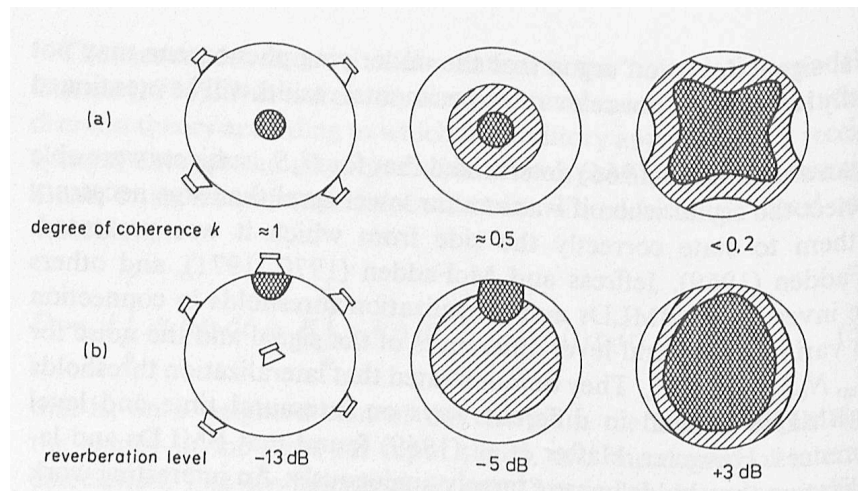


Figure 35. Importance of both the level of coherence and the level of reverberation in the creation of diffuse sound fields.

Certainly, the perception of such diffuse sound fields is especially relevant when using 8-note groups with short note durations, as in *Musical Situation 1*. The short delay

be considered when evaluating non-free sound fields, as different acoustic phenomenon take place that influence both sound perception and sound localization.

time between the successive primary sounds implies that they are more affected by the early reflections when compared to longer note durations. In addition, the radiation of the primary sounds from different positions in space creates more uncorrelated sound signals between the primary sounds themselves, primary sounds, and early and late reflections than using one sound source only. The effects of both the level differences between the reflections and primary sounds, and the influence of correlated and uncorrelated sound signals on the perception of diffuse sound fields is explained in detail in the following subchapters.

2.7.1 The influence of Correlated and Uncorrelated Sound Signals in the Creation of Diffuse Sound Fields Using Multiple Sound Sources and Reflections

Correlated sound signals occur when the sound sources are derived from one another. This can happen when a primary sound is related to a reflection with a short delay (in this case the two sound signals are similar), or a common sound signal is radiated by several loudspeakers (see figure 36).

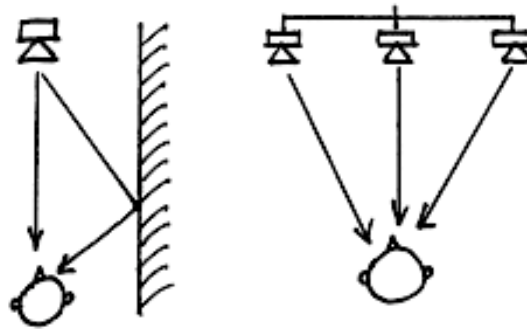


Figure 36. Addition of correlated sound sources due to an early reflection, and to multiple sound sources.¹⁴¹

In both cases, the degree of correlation between the sound sources affects the

¹⁴¹Howard *et al.*, 2001, p. 21.

amplitude of the auditory events.

Uncorrelated sound signals occur when sound comes from several sources that are not related. This may occur when the sound comes from two different instruments, or with long delay reflections (see figure 37). In the first case, the reflection presents changes in pitch, amplitude and waveform in relation to the primary sound, due to the long delay time between the two sound signals. In the second case, even when two identical instruments are playing unison, they may be generating different waveforms and small variations in frequency.

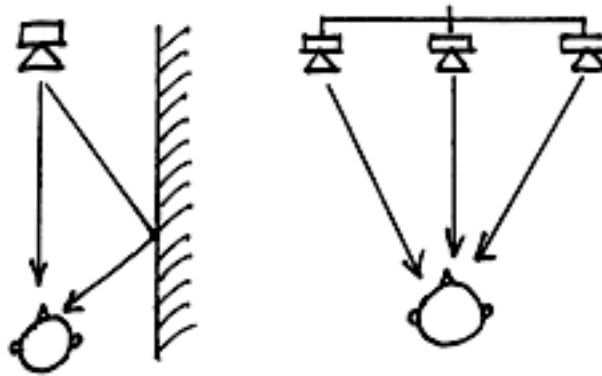


Figure 37. Addition of uncorrelated sound signals due to the delay of the reflection and to multiple different sound sources.

The division of the sustained tones into small units and their emission through eight loudspeakers situated around the room provoke more uncorrelated sound signals than when a continuous sustained tone is radiated by one sound source only. The different positions of the sound sources imply that each sound signal presents level and time differences depending on the angle of incidence to the ear.

On the other hand, correlated or uncorrelated sound signals add sound pressure levels differently. In the case of correlated sound sources, their pressure levels sum depends simply on the time shifts or phase delays (τ_{ph}) between the waves. For instance, assuming that the two signals have the same amplitude, the effect of correlated sources can vary from zero to two times the pressure level.

Adding uncorrelated sound sources is different than adding correlated sound sources. First, the resulting level depends on the power of the signals and not on their phase, which means that the combination of uncorrelated sources always increases in level. The second characteristic is that the level increase is not as high as with correlated sound sources, as power instead of sound pressure is added. As the power is proportional to the square of the pressure, the maximum amplitude increase is only $\sqrt{2}$. Another important aspect is that there are no phase cancellation effects.

Taking into consideration the level of the resonance in large halls (see figure 38) it is assumed that the increase in the pressure level produced by incoherent sound signals is important. When using multiple loudspeakers, most uncorrelated sound signals are superposed, significantly increasing the level of reverberation. Depending on the level of the primary sounds, the pressure level of the reverberation increases to the point that the primary sounds become completely masked.

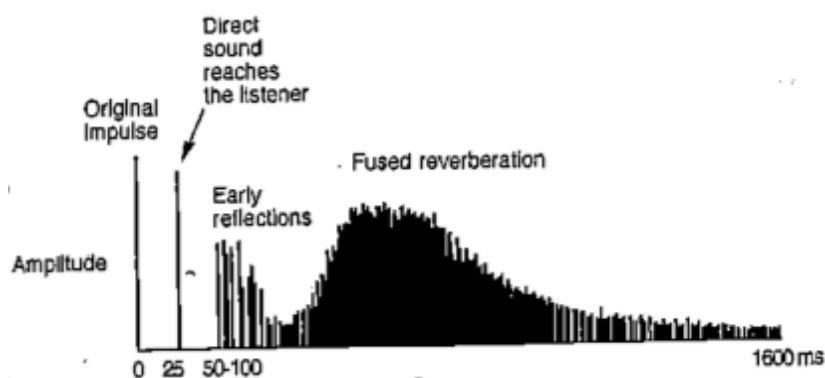


Figure 38. Impulse response envelope of a reverberant hall.¹⁴²

In any case, the compositions presented in part 2 show that using fragmented sustained tones or individual 8-note groups with short note durations radiated by multiple sound sources situated around the listener create particular levels of coherence and incoherence between the sound signals, which, together with a high pressure level of the

¹⁴² Figure 18 shows an echogram of the primary sound and reflections as collected by a microphone situated at some distance from the sound source. A series of reflections off one of the walls of the room only once appear after the primary sound, followed by those reflections that have encountered more than one wall. The last section of the echogram represents the reverberation of the room, where the reflections overlap one another. Each echogram displays a different level and time structure depending on the size of the room as well as the position of the sound source and the sound collector (Roads, Curtis, 1996, p. 474).

reflections in relation to the primary sounds, create the perception of exceptional diffuse sounds fields.

2.8 The Influence of Pitch and Echo Thresholds on the Perception of Individual Note Groups with Short Note Durations: Summing Localization and The Law of the First Wavefront

Through the experiments undertaken in this thesis, it is observed that decreasing the note duration of the notes in the 8-note groups below a certain value have important consequences for the perception of the sound attributes and sound location. First, the perception of independent auditory events decreases until only one auditory event is perceived. Second, as soon as the number of notes and the time delay between them decreases, the perception of pitch, loudness, and tone color variations between the notes in the 8-note groups becomes more difficult to differentiate or disappears. Third, as soon as the perception of sound attribute variations becomes less important, the listening concentrates automatically on variations in sound location.

For instance, test 1.1.8 shows that using note durations of 1000, 500 and 250 ms, each note in the 8-note groups is perceived as an independent auditory event, with a particular sound attribute and sound location. On the contrary, using note durations of 125, 65, 30 and 15 ms, the notes in the 8-note groups are gradually less differentiated, and the perception of different sound attributes and sound locations tends to disappear gradually.

The reason why fewer notes are perceived and at the same time sound attribute variations are less important, is related to the existence of pitch¹⁴³ and echo thresholds.

2.8.1 The Influence of Pitch Thresholds on the Perception of Sound Attribute Variations

The first consequence of decreasing the duration of the notes in the 8-note groups is that the notes are perceived as more non-pitched than pitched. As already mentioned, the perception of sound attribute variations due to sound localization depends strongly on pitch

¹⁴³ See subchapter 2.5.3.

perception.¹⁴⁴ When pitch perception is not well-defined, the possibility of perceiving sound attribute variations between notes in the 8-note groups is reduced to loudness and tone color, which are not as important as pitch variations. Therefore, the difference between the notes in the 8-note groups becomes more diffuse and difficult to distinguish.

As soon as the notes in the 8-note groups are no longer differentiated through sound attributes variations, sound localization becomes more relevant as it supplies sound dynamism¹⁴⁵ to the 8-note groups. An important experience that confirms this statement is found in test 3.1. In this test, instead of using 8-note groups where each note has the same frequency as in test 1.1.8, it uses 5-note groups with different frequencies for each note, so differences in pitch are much more relevant than in test 1.1.8. Through test 3.1 it is observed that the importance of each sound parameter follows a certain hierarchy depending on its capacity to supply a greater level of differentiation between the notes in the 8-note groups, which in turn attracts the attention of the listener. Test 3.1 shows that pitch variations seem to be the most important, followed by rhythm, tone color (timbre), loudness, and finally sound location.

In test 1.1.8, taking into consideration that

- 1) no rhythmic patterns are perceived as the notes in the 5-note groups have the same note duration, and
- 2) the perception of pitch variations due to sound localization are less important,

the listener begins to pay more attention to sound trajectories and sound locations, to the point that sound location becomes the most important parameter when, due to the decrease of the note durations, the variations in loudness and tone color are less well-perceived. On the contrary, as soon as pitch variations become more audible and active, the attention

¹⁴⁴ As already explained in subchapter 2.5, each frequency needs a certain number of cycles so a defined pitch is perceived. Decreasing the number of cycles, pitch perception becomes undefined and diffuse, until only a short impulse is perceived. A short impulse has the property that its energy is concentrated at a definite point but is distributed evenly over all frequencies.

¹⁴⁵ Sound dynamism refers here to the capacity to perceive variations in the notes in 8-note groups, and is achieved through pitch, loudness, tone color and position variations. Any acoustic sound experiments naturally variations of these parameters in time (with the exception of position variations), so they are already dynamic sounds. The extreme opposite situation is achieved using a continuous sine wave, as not even timbre variations in time occur. Here, these parameters must be added to the sound, as they don't exist in the sound itself. Here, sine waves undergo variations in these parameters through sound localization variations.

focuses on the melodic patterns created by pitch variations and sound localization becomes less important.

2.8.2 The Influence of Echo Thresholds on the Perception of Individual Note Groups with Short Note Durations

Both the temporal distance between two successive sound signals as well as the pressure level between a primary sound and its reflections determine the echo threshold after which the reflections are perceived as an independent sound signal. The second auditory event (or reflection) is called the “echo” of the first one. When any of the notes in the 8-note groups is not perceived as an independent auditory event, it has not reached the echo threshold.

Test 1.1.8 shows that with note durations of 65 ms, only five of the notes in the 8-note groups are perceived.¹⁴⁶ These five notes are perceived as one primary auditory event followed by four reflections or echoes, which in this case are the notes radiated by the sound sources. Using note durations of 30 ms only four of the notes in the 8-note-groups are perceived. The duration of the 8-note group is shorter compared to the previous example, and consists of a primary auditory event and three reflections or echoes. Finally, with note durations of 15 ms, the 8-note groups are perceived as one primary auditory event and one echo.

Figure 39 shows how the temporal space between successive notes in the 8-note groups (shown with different colors) is affected by the note duration. Decreasing the note duration implies that the velocity of the eight successive sound signals is faster.



Figure 39. Relation between the duration of the notes in the 8-note groups and velocity.

¹⁴⁶ The results of the tests presented in this thesis were realized in most cases with only one subject. Other subjects may perceive different amount of notes in the 8-note groups.

One hypothesis that could explain why fewer notes in the 8-note groups are perceived, is that the auditory system is not able to perceive two successive auditory events within a certain time delay, especially those 8-note groups with note durations of 1, 3 or 6 ms.¹⁴⁷ This assumption was totally dismissed when considering that the time delays of the 8-note groups used in the tests were above the time delays considered by the “refractory period,”¹⁴⁸ which determines the lower time delay under which the auditory system cannot activate another auditory event. Even for some of the 5-note groups in test 3.2, where the note durations are of 1 ms, the refractory period cannot explain why only one auditory event is perceived. In addition, studies on echo thresholds determine that the smallest echo thresholds are for single clicks, which under specific conditions can be less than 2 ms.

Therefore, considering that above 2 ms a reflection may be audible, the only argument that explains why fewer notes are perceived when using 8-note groups with note durations of 15, 30, or even 60 ms is the influence of the reflections of the room.

Indeed, the level of the reflections determines the echo thresholds, so they are responsible to a great extent for the number of notes in the 8-note groups that are perceived as independent auditory events. Ebata, Sone, and Nimura describe the dependence of the echo threshold on additional reflections of the room.¹⁴⁹ When the primary sound and the test reflection are at the same level, they find that the echo threshold to be at 10 ms; when a second reflection at the same level is inserted between the primary sound and the reflection, the threshold is 20-30 ms; when the interval between the primary sound and test reflection is filled with other sound signals, the threshold is as great as 200 ms. Therefore, the influence of the reflections explains why not all the notes of the 8-note groups are perceived.

In test 1.5, for instance, experiments with 8-note groups with note durations of 15 ms, spread in space using the (O) relative positions row shown in figure 40, the 8-note groups are perceived as two auditory events.

¹⁴⁷ See tests 1.3 and 3.2.

¹⁴⁸ The Refractory Period establishes that the neurons between the inner ear and central nervous system are incapable of reacting a second time for approximately 1–2 ms after being triggered. When the auditory system receives input signals at a frequency shorter than the refractory period, the number of nerve impulses triggered decreases abruptly (Blauert, 1997, p.147).

¹⁴⁹ Ebata, M., T. Sone, and T. Nimura, 1968, *On the perception of direction of echo*, J. Acoust. Soc. Amer. 44, pp. 542-547.

1.	1357-2468	5.	2413-6857
2.	4213-6875	6.	7865-1243
3.	8756-4312	7.	3618-2754
4.	5841-2376	8.	6428-7513

Figure 40. Original (O) relative position rows.

As it can be seen, the (O) relative position rows emphasize the alternation of the four aural hemispheres, left-right-front-rear (see subchapter 3.3), so the positions of the notes in the 8-note groups are more differentiated from one another.¹⁵⁰ In this case, the left-right-front-rear spatial dialog is now perceived as one attack on one side with a very short echo on the other.

With note durations of 15 ms, the perception of pitch, loudness, and tone color variations between the notes in the 8-note groups is imperceptible. The 8-note groups are perceived as one unique auditory event (the sound duration of the entire 8-note group is now 119 ms). The left-right spatial dialog is now perceived as one attack on one side with a very short echo on the other.

In this case, it is observed that the first and last notes of the 8-note groups seem to be more important than the middle notes. The question is why they are more audible than the others, considering that the echo threshold would imply that the reflections created by the middle ones would mask the late ones. The acoustic phenomenon called “inhibition of the primary sound”¹⁵¹ may explain why the middle notes are masked. Studies undertaken by Békésy¹⁵² show that under some experimental conditions, when the levels of the primary sound and the reflection are the same at the position of the listener, the primary auditory event is markedly inhibited by the reflection when delayed by 70 ms. The signals used by Békésy are 35ms pulsed sine waves, the same as those used in test 1.5.

¹⁵⁰ Test 1.1 shows that when alternating the left-right-front-rear hemispheres it is more satisfactory to perceive sound attribute and sound location variations between the notes in the 8-note groups. This is especially true concerning the perception of sound location variations. In the case of sound attributes, it is difficult to determine to what extent this alternation is better than others, as sound attribute variations of one note depend directly on how different they are perceived to be in relation to the previous note only. Listeners cannot remember sound attribute variations beyond the immediately previous note. For this reason, the (O) relative position row is designed to strengthen the alternation of the left-right hemispheres, thus making the perception of sound location variations more powerful.

¹⁵¹ Blauert, 1997, pp. 235-237.

¹⁵² Von Békésy, G., 1971, *Auditory backward inhibition in concert halls*, Science 171, p. 529-536.

Figure 41 shows the relation between the position of the auditory events with the first and last notes of the (O) relative positions (notes in bold).

-Relative distance	1357-2468 is perceived at left with a very weak echo right middle.
”	4213-6875 is perceived at right with a strong echo left-middle.
”	8756-4312 is perceived at right-rear with an echo left-middle.
”	5841-2376 is perceived at left with an echo rear-middle.
”	2413-6857 is perceived at right-rear both as first auditory event and echo.
”	7865-1243 is perceived at left-rear and the echo at left-rear.
”	3618-2754 is perceived at left and the echo at left.
”	6428-7513 is perceived at right-rear and the echo at left-middle.

Figure 41. Perceived sound locations of the notes in the 8-note groups for note durations of 15 ms, for each one of the relative positions of the (O) relative position row.

In any case, reflections have an important influence on the perception of the number, position, and sound quality of the notes in the 8-note groups when using short note durations. To what extent reflections influence the perception of each individual 8-note group depends on the echo thresholds, which are based not only on note durations, i.e. the delay time between primary sound and reflections, but also on the type of signals, the level of the primary sound and reflections, the angle of incidence to the ear, frequency, impulse width, and how steep the slopes of the signal are.

In this sense, test 3.2 exploits all the already-mentioned variables that may have an influence on echo threshold, by experimenting with successive 5-note groups with short note durations (1, 6, 11, 26, and 45 ms), different amplitudes and frequencies for each note, different relative positions (angles of incidence), and different relative and absolute distances. The variable echo thresholds contribute to a greater or lesser extent to the perception of more differentiated notes in the 5-note groups, and create a more dynamic situation compared to test 1.1.8. These note groups are used in the composition *Topos*, and are described in more detail in subchapter 4.2.3.

2.8.3 The Influence of Summing Localization and The Law of the First Wavefront in the Perception of Diffuse Sound Fields Using 8-note Groups with Short Note Durations

The influence of both the notes radiated by multiple sound sources as well as the reflections that occur below the echo threshold may have an influence on the sound pressure level of the sound signals at the ear drum. As already mentioned, sound pressure level has important consequences on the perception of pitch, loudness, and tone color as well as sound localization. In addition, it is observed that the 8-note groups with short note durations also create diffuse sound fields, which occur when the energy of the primary sound is equal to the sum of all reflections. Tests 1.1.8, 1.5, and 3.2 show that the first auditory event is followed by a “sound shadow” whose localization and sound attributes are very diffuse.

To understand why these phenomena occur it is necessary to consider the influence of summing localization and the law of the first wave front on the perception of the 8-note groups with short note durations, which depend, at the same time, on the delay times between the primary sound and the following sound signals radiated both by loudspeakers and reflections.

Studies on spatial hearing reveal that the auditory system takes into consideration coherent components of the ear input signals that arrive within up to a couple of milliseconds after the first component to determine the position of the auditory event. This phenomenon, called summing localization,¹⁵³ is very important for the perception of sound attribute and sound location variations in relation to the 8-note groups presented in this thesis. As Blauert says, “all signal components that constitute a significant part of the ear input signals within this time interval contribute to summing localization.”¹⁵⁴

Summing localization with multiple sound sources can also occur, and it establishes as well the position of the auditory events. In the tests presented in this thesis, sound signals are presented through eight loudspeakers spread around the listener in an octagon. The smallest time delay between the sound signals radiated by the loudspeakers is 1 ms. Consequently, only the early reflections occurring after the primary sound may influence

¹⁵³ Blauert, 1997, p. 204.

¹⁵⁴ Ibid., p. 272.

sound localization. In addition, the influence of the reflections on sound localization depends on their pressure level in relation to the primary sound.¹⁵⁵

In the case of two sound signals arranged in the standard stereophonic arrangement, when the time difference of the two signals at the ear drum differ by approximately 1 ms, the auditory event reaches the location of the loudspeaker that radiates the sound signal first, and remains there for longer time delays until the auditory event is split in two sound signals. The fact that the auditory event remains in the direction of the first sound signal means that the signal components that arrive at the ear drum first are taken into consideration, and the other ones are suppressed in the interpretation process. This effect is called the law of the first wavefront.¹⁵⁶ As Blauert states,

The law of the first wave front — that is, the fact that the reflection is not taken into consideration in forming the direction of the auditory event — points to the existence of inhibitory processes in hearing. Clearly components of the ear input signals that originate with the reflection are not fully evaluated; in one way or another, their evaluation is totally or partially suppressed.¹⁵⁷

However, studies on the law of the first wave front confirm that as soon as the delay time is increased beyond 1ms, further changes in the auditory event beyond sound

¹⁵⁵ In this sense, it can occur that below a certain pressure level reflections may be completely masked by the primary sound, which mean that they have no influence on either sound attributes or sound location. Figure 42 shows some thresholds of perception that occur with the standard stereophonic arrangement (base angle $\alpha = 80^\circ$), for continuous speech (5 syllables per second) and a primary sound level of ca. 50 dB.

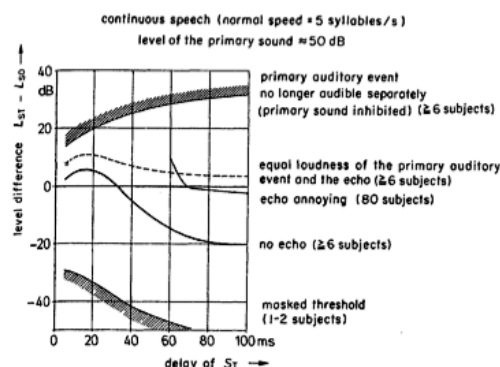


Figure 42. Comparison of various thresholds for reflections.

¹⁵⁶ Cremer, L., 1948, *Die wissenschaftlichen Grundlagen der Raumakustik* [The scientific foundations of architectural spaces], vol. 1, S. Hirzel Verlag, Stuttgart.

¹⁵⁷ Blauert, 1997, pp. 229-230.

localization are audible: the tone color of the auditory event changes, and its spatial extension increases. In addition, the “center of gravity” of the auditory event shifts toward the direction of incidence of the reflection, until it finally separates into two auditory events in different directions.

Considering that the notes in the 8-note groups used in the tests are radiated at delay times that exceed 1 ms, the law of the first wavefront confirms that both notes in the 8-note groups and reflections occurring at delay times above summing localization and below the echo threshold may influence the perception of sound localization and sound attributes as well as spatial extension. As shown in test 3.2, these variations are perceived clearly when using 8-note groups with different note durations.

At the same time, as the sound signals corresponding to the notes in the 8-note groups have the same pressure level, summing localization and the law of the first front also explain why the 8-note groups with short note durations are perceived as diffuse sound fields. This is the case of the 8-note groups in test 1.5, where the 8-note groups using 60, 30, and 15 ms note durations are perceived as one sound impulse more than the sum of eight independent pitches. Thus, the perception of sound attribute variations as well as sound localization become more complex and difficult to grasp, and the first note and last notes are accompanied by a sound shadow.

Chapter 3. TEMPORAL AND SPATIAL ORGANIZATION OF THE 8-NOTE GROUPS: SOUND LOCATION AND SOUND-SPACE DENSITY

The previous chapter explains why a tone is perceived with pitch, loudness, and tone color variations depending on the direction and distance of the sound source in relation to the ear. The importance of this phenomenon in musical composition is that the attributes of a sound can be defined to some extent by their position in space.

This chapter proposes a formal organization of sounds, so the perception of such sound attribute variations involved in spatial hearing is emphasized. It introduces concepts and techniques such as sound division, relative and absolute distances, relative and absolute positions, and sound-space densities, which in addition to the perception of sound attribute variations, permit the creation of rhythm and texture variations. These concepts are used for one sole purpose: to maximize the impact of space and sound localization on the perception of sound attributes.

First of all, to perceive the sound attribute variations derived from sound localization, it is necessary that the same sound is radiated successively from different locations. With this purpose, experiment 1 presents several tests where a sine wave is fragmented in eight small units, or notes, which are gathered into 8-note groups, each one of which is radiated through one of the eight loudspeakers (see figure 19, p. 69). Figure 43 shows the division of a tone in small units spread through eight audio tracks (Aud. 1, 2, 3, etc.).

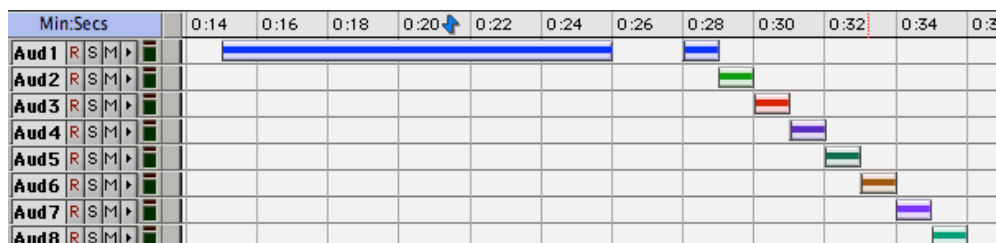


Figure 43. Graph showing a Pro Tools session with the division of one tone in eight units spread into eight independent tracks.

The audio track number corresponds to the loudspeaker number. Therefore, by assigning an audio track to each one of the notes in the 8-note groups a spatial position is automatically assigned, which in this case corresponds to the loudspeaker arrangement shown in figure 19 (p.69).

Once the continuous tone is divided into eight notes, it is necessary to assign a specific audio channel to each note. The organization of the notes in the 8-note groups in space is determined by relative position, which designates a spatial position for each one of the notes in the 8-note groups. In figure 39 above, the notes in the 8-note groups follow the relative position 1234-5678, as they are organized in space so note 1 is assigned to audio 1, note 2 to audio 2 and so on. Using relative position 1357-2468 means that note 1 is assigned to audio 1, note 2 to audio 3, note 3 to audio 5 and so on (see figure 44).

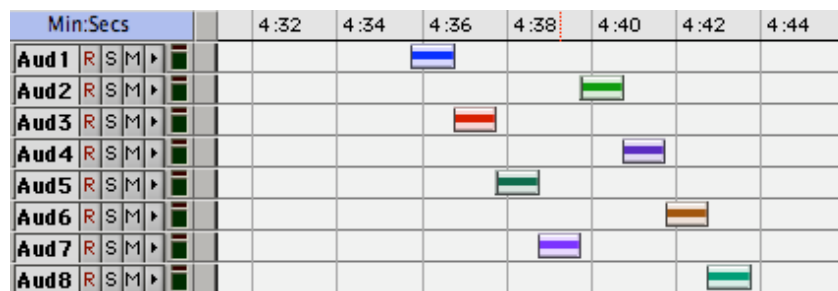


Figure 44. Graph showing the organization of the notes in the 8-note groups following the relative position 1357-2468.

An important characteristic of the relative position is that it always uses eight loudspeakers, i.e. the notes in the 8-note groups must go through the eight sound sources before they repeat one sound source.

When the 8-note groups are organized using less than eight sound sources, they are perceived with different textures and rhythms in addition to sound attribute variations. The quality of these textures and rhythms depend mainly on how many sound sources are used to radiate the notes in the 8-note groups. The absolute position determines how many and which sound sources are used. As we will see, the absolute position reorganizes the original relative position using less than eight sound sources. How this is done is explained later in this chapter.

Each absolute position implies a particular spatial distance or extension between the notes in the 8-note groups, which depends on how many loudspeakers radiate the notes in the 8-note groups as well as how separated are they in space. The term “sound-space density” defines the relation between the notes in the eight note groups and the “real” space they occupy, so when the notes in the 8-note groups are radiated by two loudspeakers, sound-space density is $8/2$, i.e. eight notes, two loudspeakers. As shown in experiment 4, sound-space density variations are very important to the perception of rhythm and texture variations in successive 8-note groups.

All these concepts are explained in detail in the following subchapters.

3.1 Why Divide a Sustained Tone in Small Units?

As the purpose of this thesis is to investigate the perception of sound attribute variations involved in the processes of sound localization, it is necessary that sound is perceived coming from different angles and distances. Therefore, the first and most relevant characteristic of the compositions included in the second part of this thesis is that they are based on the fragmentation or division¹⁵⁸ of tones into small sound units that I call “notes”, gathered together into groups of eight notes called 8-note groups, and radiated through eight loudspeakers situated around the listener.

Both the experiments and the compositions included in this thesis use eight sound sources arranged in a circle around the listener following the approximate shape of a regular octagon. Each loudspeaker is numbered, corresponding to a specific vertex of the octagon (see Figure 19, p. 69). The number of notes inside the 8-note groups coincides

¹⁵⁸ The term “divisionism” was used to describe the pictorial technique characteristic of Neoimpressionism, which consists of separating colors into individual dots or patches. Through divisionism, each color is not achieved by mixing pigments but by optical interaction of individual color points separated from one another by a certain amount of white space. The white space between color points has an important optical influence on the resultant overall color, as it may be perceived differently depending on the space between points. At the same time, the figures are perceived with a certain degree of “airiness” due to the white “empty” spaces between color points (Homer, William I., 1964, *Seurat and the Science of Painting*, Cambridge, MA, The MIT Press). This technique has partially inspired this research. Like pointillism, each tone is constituted by the sum of sound fragments radiated by multiple loudspeakers separated from one another by a certain amount of “real” space. The insertion of “real” space between sounds influences not only the perception of the sound attributes, but also provides each sustained tone with a certain “airiness” that is not perceived when sound is radiated by one sound source only.

with the maximum number of loudspeakers available at CIME, where I realized all the experiments as well as compositions. Although fewer loudspeakers could be used, eight sound sources proved to be an appropriate number, as each aural hemisphere is represented by two sound sources. Moreover, the experiments and compositions proved that eight sound sources was sufficient to perceive the sound attribute variations produced together with sound localization.

Each sound source represents a different angle of incidence in relation to the subject, who is situated at the centre of the octagon. The sound units or notes are organized in groups of eight units called 8-note groups, according to the maximum number of sound sources. When the notes inside the 8-note groups are played one after the other through different loudspeakers, each note reaches the ear from a different angle, and the transfer functions occurring at the external ear permit the perception of pitch, loudness, and tone color variations between them.

3.2 Sound-Space Density

Tests 1 and 2 show the influence of spatial hearing in relation to sound perception using 8-note groups with different frequencies and note durations radiated always through eight loudspeakers. However, the notes in the 8-note groups can be radiated by fewer loudspeakers, which would imply that the same loudspeaker radiates two or more notes. Tests 1.5 and 1.6 demonstrate that using different amounts of loudspeakers, the same 8-note groups are perceived with important rhythm and texture variations.

Sound-space density refers to the number of loudspeakers used to radiate the 8-note groups. As the loudspeakers are spread in space, the number of loudspeakers used to radiate the 8-note groups defines the spatial extension of the notes in the 8-note groups, and the distance and separation between them. Therefore, the term sound-space density is used to define a particular relation between the notes in the 8-note groups, the number of loudspeakers used to radiate them, and the spatial extension they occupy. As shown in test 4.1, sound-space density variations are very important to perceive sound attribute, rhythm, and texture variations, which occur when the same 8-note group is radiated successively using different amounts of loudspeakers.

The most important feature of such variations is that listening establishes a relation

between the perception of sound attribute, rhythm, and texture variations of the notes in the 8-note groups and the movement of sounds through different positions and sound-space densities. The cause-effect relation between the position and spatial density of sound on one hand, and the perception of sound attribute, rhythm, and texture variations on the other, is possibly the most important relevant achievement in this thesis.

Two numbers define sound-space density:

- the first number indicates the number of notes inside each “note group”. In this thesis only note groups with eight or five notes are used.
- the second corresponds to the number of sound sources used to radiate them. In all cases the maximum number of sound sources is eight.

Therefore, the possible sound-space densities of the 8-note groups are $8/1$, $8/2$, $8/3$, $8/4$, $8/5$, $8/6$, $8/7$, and $8/8$, and the ones corresponding to the 5-note groups are $5/1$, $5/2$, $5/3$, $5/4$, and $5/5$. For instance, when the notes in the 8-note groups are radiated by one loudspeaker only, the sound-space density is $8/1$, which represents the highest sound-space density possible (see figure 13 (a), p. 58). On the contrary, when the notes in the 8-note groups are radiated by eight different sound sources, the resulting sound-space density is $8/8$, thus representing the minimum sound-space density possible (see figure 13 (b), p. 58).

Figure 45 shows different positions of the notes in the 8-note groups using the same sound-space density $8/5$.

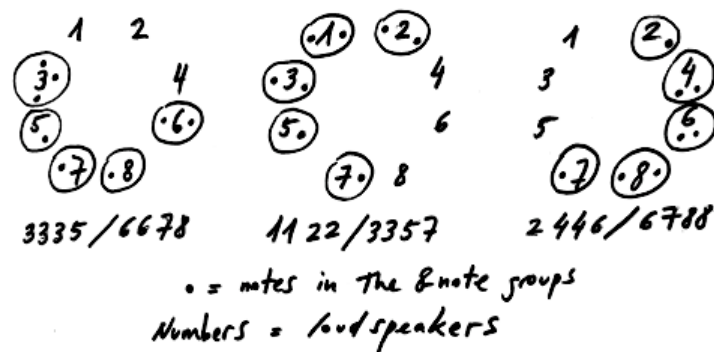


Figure 45. Graph of different spatial organizations of the notes in the 8-note groups using sound-space density $8/5$.

As it can be seen, the same sound-space density can use different combinations of loudspeakers.¹⁵⁹ Each one of these spatial arrangements implies a different perception of the same 8-note group in relation to sound attributes, and when they are played one after the other they create rhythm and texture variations.

Sound-space density can also be used to supply transparency and clarity to polyphonic textures, especially when the principle of no overlapping is respected (see subchapter 3.6). This principle is achieved by using complementary sound-space densities and spatial positions, which allow for several simultaneous textures while preventing their superposition in space, namely that the same loudspeaker radiates two or more textures at the same time.

Figure 46 shows how simultaneous textures are organized using complementary sound-space densities.

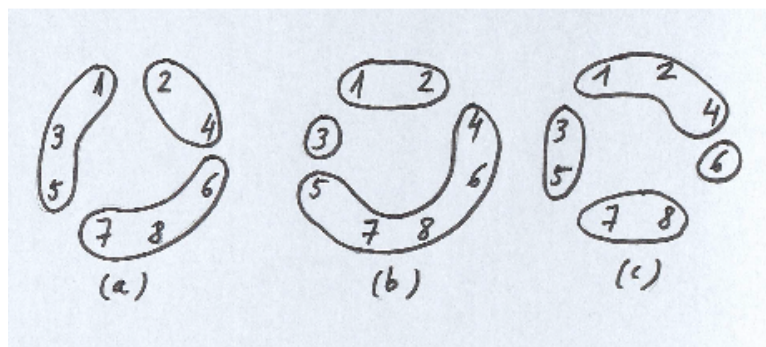


Figure 46. Graph of complementary sound spaces.

In example (a) three different layers use contiguous loudspeakers 1-3-5, 2-4, and 7-8-6, which spatially differentiate them. In example (b) they use loudspeakers 1-2, 3, and 5-7-8-6-4. In example (c) four layers use loudspeakers 1-2-4, 3-5, 6, and 7-8. The textures and other sound materials explained in chapter 4 constantly change their position and sound-space density through complementary sound-space densities, so each texture is more differentiated from the others and improves the perception of sound attribute, rhythm, and

¹⁵⁹ Which loudspeakers are used and how they are organized is defined by absolute position, which is explained in subchapter 3.3.

texture variations.

Sound-space density refers to the number of loudspeakers used to radiate the 8-note groups. The exact temporal and spatial organization of the notes in the 8-note groups for each sound-space density is defined by relative and absolute positions. These concepts are explained in the detail in the next subchapters.

3.3 Temporal and Spatial Organization of the Notes in the 8-note Groups through Relative and Absolute Positions

Relative and absolute positions organize the temporal and spatial position of the notes in the 8-note groups in relation to the position of loudspeakers. Indeed, the relative and absolute positions determine which loudspeaker radiates each one of the notes in the 8-note groups, and at the same time, which loudspeaker sounds first in relation to the others. In this sense, the temporal organization of the sound sources and the spatial organization of the 8-note groups occur simultaneously and one cannot be dissociated from the other.

3.3.1 Relative Position

The most important difference between relative and absolute position is that the relative position always assigns a loudspeaker to each one of the notes in the 8-note groups using always sound-space density 8/8 and absolute position 1234-5678.¹⁶⁰ This research includes many tests that experiment with the consequences of different relative positions in relation to sound perception and sound localization. Through these tests it is possible to determine which relative positions are more dynamic,¹⁶¹ i.e. the notes in the 8-note groups are more differentiated from one another in relation to sound attribute and sound location variations.

Test 1.1.6 and 1.5 evaluate the perception of sound attribute variations when sound

¹⁶⁰ See subchapter 3.3.2.

¹⁶¹ The term “dynamism” refers to the amount of variations perceived when the same 8-note group is played successively through different relative and absolute positions as well as sound-space densities, which can occur in relation to sound attribute, rhythm, texture, and sound location variations. The more variations are perceived, the more dynamic are the successive 8-note groups.

moves

- 1) alternating the left-right aural hemispheres,
- 2) alternating the front-rear aural hemispheres, and
- 3) alternating the left-right and front-rear aural hemispheres simultaneously.

Test 1.5 shows that when the notes in the 8-note groups are organized in space alternating the left-right aural hemispheres, it is possible to perceive more contrasting sound attribute and sound location variations than when two successive notes remain in the same hemisphere. This statement is especially relevant when using short note durations, as sound location is more evident for the listening than sound attribute variations.

For instance, using the relative position 8756-4312 (note 1/ loudspeaker 8, note 2/ loudspeaker 7, and so on) the left-right aural hemispheres change four times, while using the relative position 1372-4865 they change two times (see figure 47).

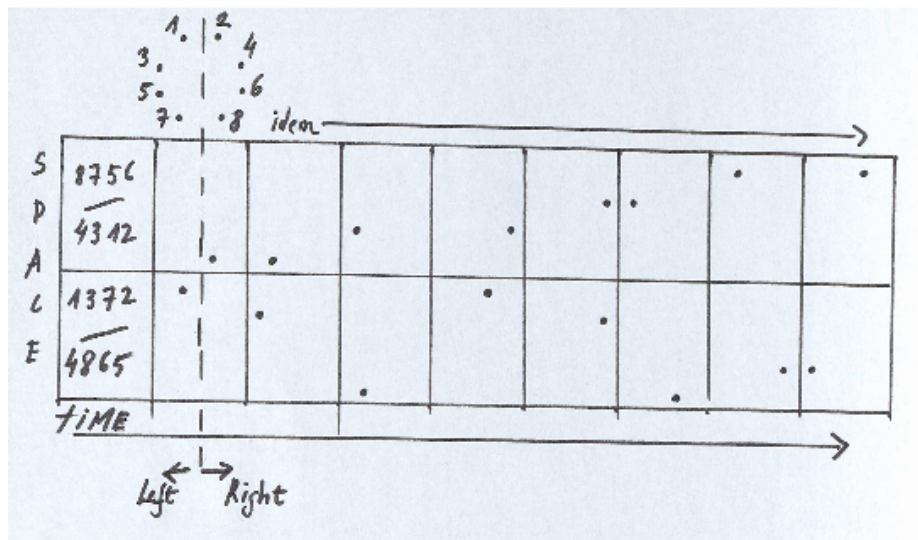


Figure 47. Differences in spatial dynamism between left-right aural hemispheres using relative positions 8756-4312 and 1372-4865

When using 8-note groups with long note durations (greater than 125 ms), sound attribute variations are very well perceived, and they become more important for listening than sound location variations.

It is observed that the spatial trajectories of the notes in the 8-note groups are easily recognizable when using few relative positions, and after some time they become monotonous and repetitive. This is due to the fact that, besides recognizing the same spatial trajectories, the notes in the 8-note groups are also perceived with the same melodic contours produced by the same pitch, loudness, and tone color variations. Therefore, it is convenient that the 8-note groups change their relative position constantly, at least to the point that memory can no longer recognize similar trajectories.

Therefore, to guarantee the maximum dynamism concerning sound localization and the perception of sound attribute variations, the notes in the 8-note groups follow eight relative positions rows, which guarantee the alternation of the four hemispheres left-right-front-rear. These relative positions are referred as the original (O) relative position row (see figure 40, p. 105).

Test 4.1 shows that using short note durations, the (O) relative position rows create rhythmic patterns, which appear periodically and at the same position in space. This situation is especially annoying when trying to create uniform textures using successive 8-note groups. In order to avoid such repetitive rhythmic situations, the entire eight original (O) relative position rows are repeated thus:

- 1) Retrograde (R), so the entire eight (O) relative position rows are played backwards, from the last note in the last 8-note group to the first of the first 8-note group,
- 2) Inversion (I), so that track 1 becomes track 8, track 2 becomes 7, etc. (see figure 6, p. 37),
- 3) Retrograde of the Inversion (RI), where the entire (I) relative position rows are played in retrograde.

As it can be seen in figure 48, the first row of the (O) relative position rows corresponds to the last row of the (R) relative position rows but in retrograde, the second to the seventh and so on. At the same time, the first row of the (I) relative position rows corresponds to the last row of the (RI) relative position rows but in retrograde, the second to the seventh and so on. Figure 49 shows the resulting series as it appears in Pro Tools. The first row corresponds to the Original (O), the second to the Retrograde (R), the third to

the Inversion (I) and the fourth to the Retrograde of the Inversion (RI).

	Original (O)	Retrograde (R)	Inversion (I)	Retrograde of the Inversion (RI)
1-	1357-2468	3157-8246	8642-7531	6842-1753
2-	4213-6875	4572-8163	5786-3124	5427-1836
3-	8756-4312	3421-5687	1243-5687	6578-4312
4-	5841-2376	7586-3142	4158-7623	2413-6857
5-	2413-6857	6732-1485	7586-3142	3267-8514
6-	7865-1243	2134-6578	2134-8756	7865-3421
7-	3618-2754	5786-3124	6381-7245	4213-6875
8-	6428-7513	8642-7531	3571-2486	1357-2468

Figure 48. Original (O), Retrograde (R), Inversion (I), and Retrograde of the Inversion (RI) relative position rows.

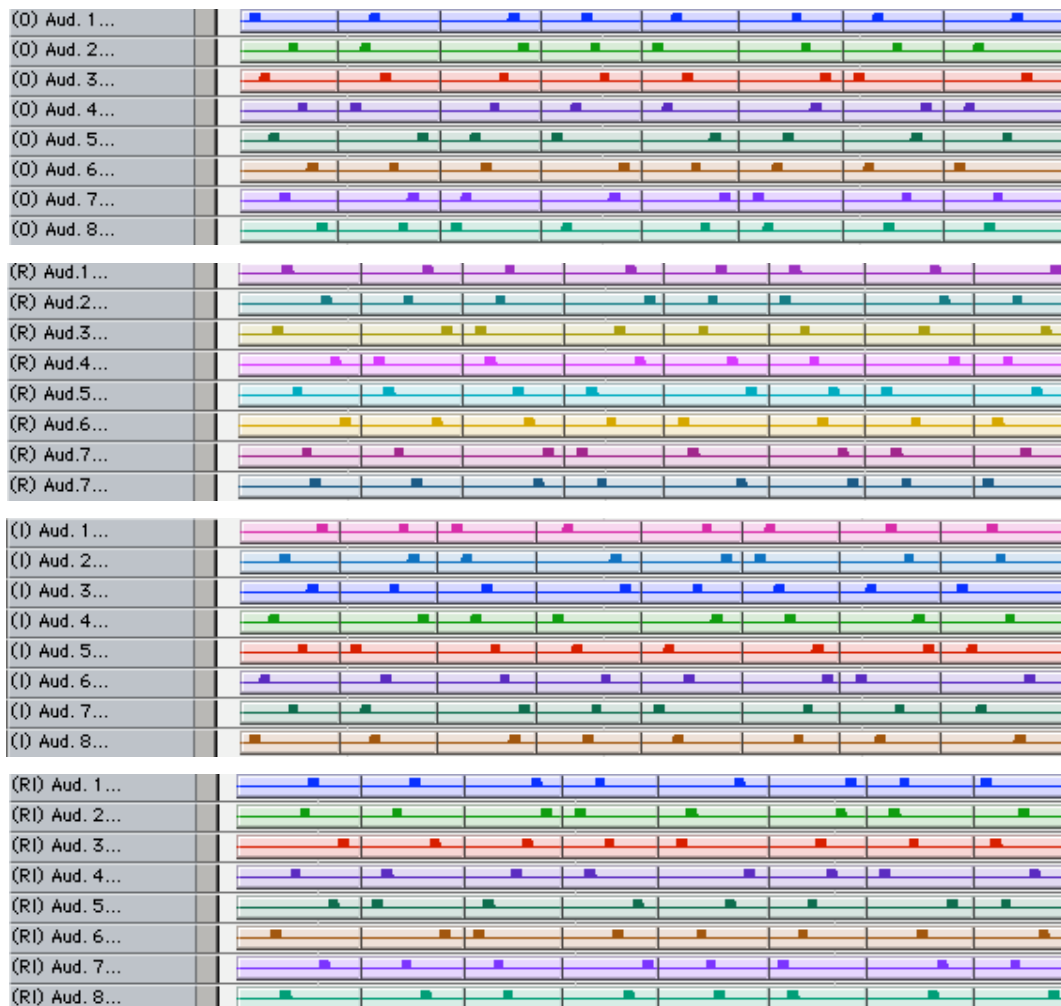


Figure 49. Pro Tools image showing the (O), (R), (I), and (RI) relative positions rows.

Applying these relative position variations, the rhythmic patterns that were perceived when repeating the (O) relative position rows disappear. Therefore, using sound-space density 8/8 and the (O), (R), (I), and (RI) relative position rows permit the creation of uniform textures, as sound trajectories are constantly renewed, and the perception of rhythmic patterns or the possibility to recognize the same spatial trajectories of the notes in the 8-note groups is avoided. These rows are used for both the tests and compositions.

3.3.2 The Absolute Position

The absolute position reorganizes the relative position so less than eight loudspeakers radiate the notes in the 8-note groups. When the absolute position is 1234-5678, the temporal and spatial organizations of the notes in the 8-note groups coincide with the ones determined by the relative position, as the initial (O), (R), (I) and (RI) relative positions use always absolute position 1234-5678 (see figure 43 and 44, p. 110-111).

Experiment 4 shows the importance of the absolute position variations to the perception of sound attribute, rhythm, texture, and sound localization variations of both individual and successive 8-note groups, as well as to the differentiation of the layers of a polyphonic musical situation in order to confer musical clarity and transparency and to mold sounds with a particular shape and sound directionality. Test 4.4, for instance, uses a row with twelve different absolute positions. The absolute positions, like the previous relative positions, create contrasting sound locations between the four aural hemispheres, as well as contrasting sound-space densities (see figure 50).

1-	7777 / 7777	8/1	5-	3333 / 5555	8/2	9-	4444 / 4444	8/1
2-	2244 / 6688	8/4	6-	3333 / 3333	8/1	10-	2226 / 6688	8/3
3-	2222 / 4444	8/2	7-	6666 / 8888	8/2	11-	6666 / 6666	8/1
4-	2222 / 2222	8/1	8-	1133 / 5577	8/4	12-	1111 / 1111	8/1

Figure 50. Example of twelve absolute position rows used in tests 4.4.1.

As it can be seen, the same sound-space density is repeated several times using

different loudspeakers or sound locations. For instance rows 3, 5, 9, and 11 use sound-space density $8/2$ radiated from loudspeakers 8-6, 1-3, 3-5, and 1-2 respectively (see figure 51).

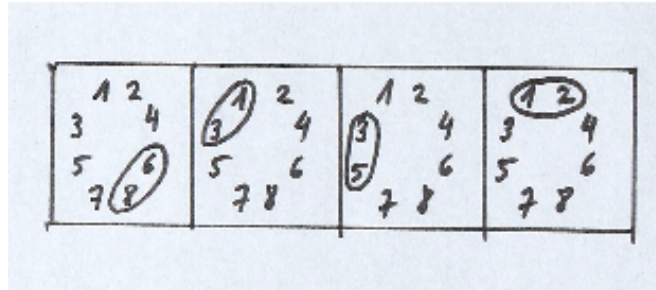


Figure 51. Spatial arrangement of the same sound-space density $8/2$ radiated through different loudspeakers.

In this case, although the 8-note groups are perceived with the same texture, using different sound locations prevents having exactly the same auditory experience:

- first, each one of them is perceived from a different position,
- second, the perception of the same 8-note groups with the same sound-space density from different angles of incidence to the ears distinguishes them with a particular pitch, loudness, and tone color, and
- third, in the case the four 8-note groups are played consecutively one after the other, the space confers a spatial rhythm.

In addition, using different relative positions while maintaining the same absolute position may also produce differences in the perception of the same 8-note groups. Test 1.6, for instance, shows that contrasting absolute positions create textures with an internal rhythm, specially using note durations of 130, 60, and 30 ms. However, the perception of such rhythm is more evident as soon as the relative positions are different. This is due to the fact that the relative position determines the position of the first and last notes, which are the most important auditory events regarding sound localization when using 8-note groups with short note durations.

How relative position influences absolute position is explained in the next

subchapter.

3.4 The Sum of Relative and Absolute Positions in the Temporal and Spatial Organization of the Notes in the 8-note Groups

To describe how the relative and absolute positions determine the temporal and spatial organization of the notes in the 8-note groups, it is necessary to explain the methodology used.

Both the temporal and spatial organization of the 8-note groups is done through Pro Tools. The first step consists of organizing the tracks in a session, so each track is assigned to one loudspeaker. As the first tests of this research use only relative positions, all eight loudspeakers are used. Every time the eight loudspeakers are used they are organized in the tracks successively from 1 to 8 using the absolute position 1234-5678. In figure 52, each audio track is radiated by a different loudspeaker, so audio 1 is radiated through loudspeaker 1, audio 2 through loudspeaker 2, and so on.

Track 1	output 1	(loudspeaker 1)
Track 2	output 2	(loudspeaker 2)
Track 3	output 3	(loudspeaker 3)
Track 4	output 4	(loudspeaker 4)
Track 5	output 5	(loudspeaker 5)
Track 6	output 6	(loudspeaker 6)
Track 7	output 7	(loudspeaker 7)
Track 8	output 8	(loudspeaker 8)

Figure 52. Organization of the tracks, outputs, and loudspeakers in Pro Tools.

As it can be seen, the outputs and loudspeakers follow the arrangement dictated by the absolute position, so outputs and absolute positions are the same. This is applicable to all the following examples using tracks, outputs, and loudspeakers.

Figure 53 shows the spatial organization of the notes in the 8-note groups following

the previous absolute position 1234-5678 and the (O) relative position row 1357-2468 (see figure 48, p.119).

			Notes in the 8-note Groups	
Track 1	output 1	(loudspeaker 1)	1	
Track 2	output 2	(loudspeaker 2)		5
Track 3	output 3	(loudspeaker 3)	2	
Track 4	output 4	(loudspeaker 4)		6
Track 5	output 5	(loudspeaker 5)	3	
Track 6	output 6	(loudspeaker 6)		7
Track 7	output 7	(loudspeaker 7)	4	
Track 8	output 8	(loudspeaker 8)		8

Figure 53. First example showing the relation between relative and absolute positions.

This example should be considered as having two coordinates: the vertical axis representing space, i.e. audio tracks and loudspeakers, and the horizontal axis time, i.e. successive notes in the 8-note groups. When the notes in the 8-note groups are displaced in the axis of coordinates following a specific relative position, the vertical axis organizes the notes in the 8-note groups in space; each note is assigned to a specific loudspeaker, following the order specified by the relative position. At the same time, the horizontal axis organizes each loudspeaker in time, so the first sound radiates from loudspeaker 1, the second from loudspeaker 3, etc.

Following the octagonal organization of the loudspeakers in space shown in figure 19 (p. 69), the notes in the 8-note group are organized so tracks 1, 3, 5, and 7 sound in the left. aural hemisphere, while 2, 4, 6, and 8 sound in the right. Therefore, in the example above the four loudspeakers in the left hemisphere radiate the notes in the 8-note groups first, followed by the four loudspeakers at the right. At the same time they describe two front-rear sound trajectories, i.e. the four sound sources at the left hemisphere describe a front-rear discontinuous movement, as do the four sound sources at the right (figure 54).

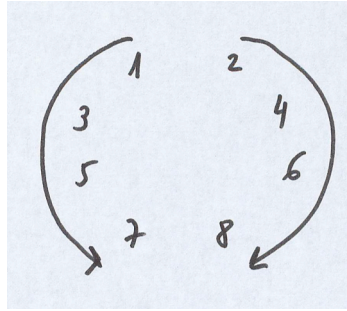


Figure 54. Front-rear discontinuous movement described by the (O) relative position row n.1.

Changing the absolute position reorganizes the temporal and spatial organization established by the relative position. Figure 55 shows how the previous absolute position 1234-5678 changes to the absolute position 6666-8888. The original sound-space 8/8 becomes 8/2, so the spatial extension of the 8-note group is reduced dramatically. Consequently, the perception of the same relative position is very different compared to the previous example, as only two loudspeakers are used (6 and 8), and both are situated in the right-rear aural hemisphere.

Notes in the 8-note Groups			
Track 1	output 6	(loudspeaker 6)	1
Track 2	output 6	(loudspeaker 6)	5
Track 3	output 6	(loudspeaker 6)	2
Track 4	output 6	(loudspeaker 6)	6
Track 5	output 8	(loudspeaker 8)	3
Track 6	output 8	(loudspeaker 8)	7
Track 7	output 8	(loudspeaker 8)	4
Track 8	output 8	(loudspeaker 8)	8

Figure 55. Second example showing the relation between relative and absolute positions.

The spatial and temporal organization of the notes in the 8-note group is the following: first, two notes appear at loudspeaker 6, then two notes at loudspeaker 8, followed again by two notes at loudspeaker 6, and two notes at loudspeaker 8 (figure 56).

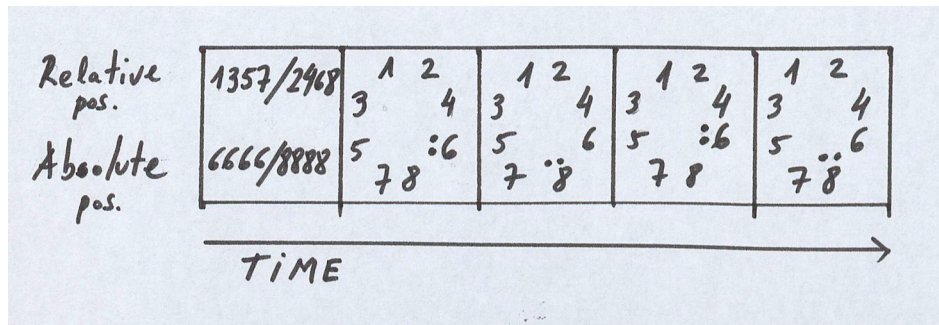


Figure 56. Graph of the temporal and spatial organization of the notes in the 8-note groups using relative position 1357-2468 and absolute position 6666-8888.

The next example shows that changing the absolute position to 1133-6688 while keeping the same relative position 1357-2468 produces a new spatial and temporal organization of the notes in the 8-note groups (see Figure 57).

Notes in the 8-note Groups			
Track 1	output 1	(loudspeaker 1)	1
Track 2	output 1	(loudspeaker 1)	5
Track 3	output 3	(loudspeaker 3)	2
Track 4	output 3	(loudspeaker 3)	6
Track 5	output 6	(loudspeaker 6)	3
Track 6	output 6	(loudspeaker 6)	7
Track 7	output 8	(loudspeaker 8)	4
Track 8	output 8	(loudspeaker 8)	8

Figure 57. Third example showing the relation between relative and absolute positions.

In this example the aural right-left hemispheres are used again, although the spatial trajectory of the notes in the 8-note group is different compared to the first example. The spatial and temporal organization of the notes in the 8-note group is the following: the first two notes appear on loudspeakers 1 and 3, then two notes on loudspeakers 6 and 8. This sound trajectory is repeated again for the next four notes (see figure 58).

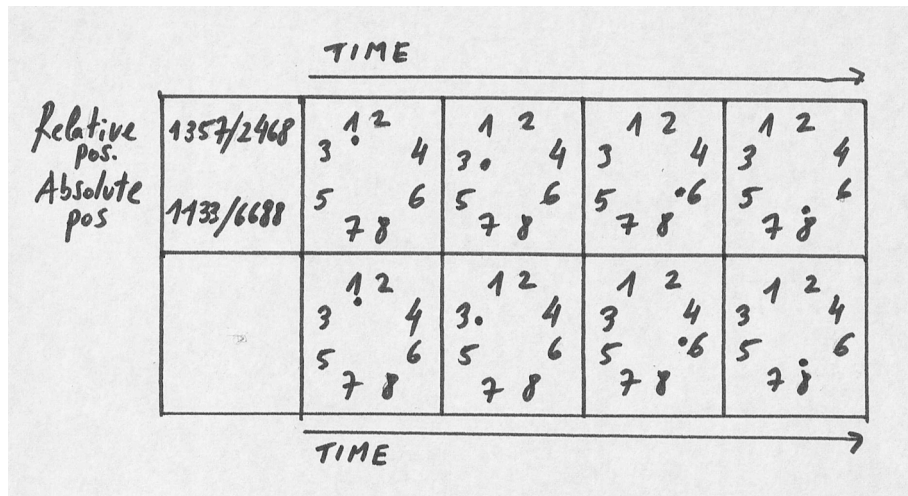


Figure 58. Graph of the temporal and spatial organization of the notes in the 8-note groups using absolute position 1133-6688 and relative position 1357-2468

Finally, the perception of sound attribute, rhythm, texture, and sound location variations can also be achieved by changing the relative position while keeping the same absolute position. However, this option is less efficient in the perception of sound attribute, rhythm, texture, and sound-location variations. Indeed, test 4.1 shows that when playing the same (O) and (R) relative-position rows with the same absolute position, the 8-note groups are perceived almost identically. In spite of this, relative position does provide enough variations to the successive 8-note groups that they are not perceived as exactly the same.

Hence, the perception of sound attribute (i.e. pitch, loudness, and tone color), rhythm, and texture variations associated with the movement of sounds through different sound locations and sound sound-space densities can be achieved by

- 1) keeping the same relative position while going through different absolute positions,
- 2) changing the relative position while keeping the same absolute position, or
- 3) changing both the relative and the absolute positions.

Test 1.6 proves that simultaneous relative and absolute position variations accentuate

the perception of sound attribute, rhythm, and texture variations between successive 8-note groups. However, the perception of such variations depends also on the frequency and note duration of the notes in the 8-note groups, as well as on their relative and absolute distances.¹⁶² These variables are discussed in the following subchapter.

3.5 The Influence of Note Durations, Relative and Absolute Distances, and Relative and Absolute Position Variations on the Perception of Sound Attribute, Texture, and Sound Localization Variations.

Experiment 1 presents several tests using 8-note groups with different note durations, relative distances, and relative positions, showing that the perception of sound attribute variations depends on the frequency, note duration, relative position, and relative distance of the notes in the 8-note groups.

First, an optimal perception of sound attribute variations between the notes in the 8-note groups depends to a great extent on pitch variations, as they are more important compared to loudness and tone color. As already mentioned in subchapter 2.5.3, the note duration threshold for pitch perception is different for each frequency, so each frequency needs a certain note duration before pitch is fully perceived.

Second, tests 1.1.5 and 1.2.5 prove that the perception of sound attribute variations produced by sound localization is inversely proportional to the relative distance. It is observed that the perception of sound attribute variations between the notes in the 8-note group depends on how differently a particular note is perceived in relation to the immediate previous one. Sound attribute variations produced by different sound locations are so subtle that it is impossible to memorize and compare the sound attribute differences of two successive notes over long periods of time. As soon as the relative distance increases beyond 1000 ms, the perception of pitch, loudness, and tone color variations become less recognizable and tend gradually to disappear.

In this respect, test 1.1.5 shows three situations where the same 8-note groups are presented with a relative distance of (1) 0 ms, (2) $1 \approx 3$ seconds, and (3) $3 \approx 6$ seconds.

¹⁶² As already mentioned, relative distance refers to the distances between the notes in the 8-note groups while absolute distance refers to the distances between the 8-note groups themselves.

Compared to 0 ms, sound attribute variations become gradually less perceptible until only small variations in loudness are perceived.

Third, using irregular absolute distances increases the perception of dynamism between the 8-note groups. Test 1.5 shows that using short and almost regular absolute distances, sound dynamism is less satisfactory than using irregular absolute distances. In this sense, the optimal absolute distances vary depending on note duration. Longer note durations, for instance, permit the use of longer absolute distances so the perception of sound attribute, rhythm, texture, and sound location variations between the successive 8-note groups is still recognizable.

3.6 Molding Sounds in Space Using Relative and Absolute Position Variations: The “Principle of No Overlapping”

To conclude this chapter dedicated to relative and absolute position, it is worth mentioning that they represent the movement of the notes in the 8-note groups in space, creating different sound trajectories and, in the case of textures, molding the 8-note groups into different spatial shapes and sound directionalities. These phenomena are especially relevant in the composition *Topos* and *Polyphonic Continuum*.

The piece *Topos*, for instance, presents individual or successive 5-note groups with short note durations radiated either by one unique sound source, or spread in space using the so-called “right-left sound-space dilation rows”. Figure 59 represents the dilation of successive 5-note groups in the composition *Topos* (00’50’’ to 01’25’’).

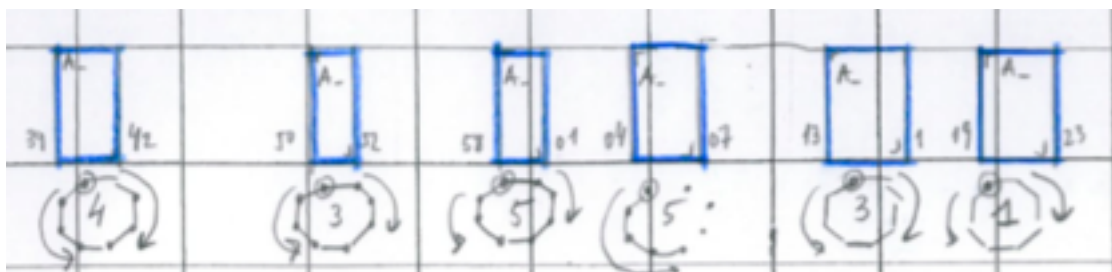


Figure 59. Detail of the graphic score of *Topos* showing the “right-left sound-space dilation rows” for the attacks (00’50’’ to 01’25’’).

The main characteristic of these rows is that they expand the spatial extension of the 5-note groups by alternating the left-right hemispheres. The resulting auditory experience is similar to the visual image of water drops breaking and spreading their mass in all directions when touching the floor.

Figure 60 shows how different textures are molded in space using different absolute positions.

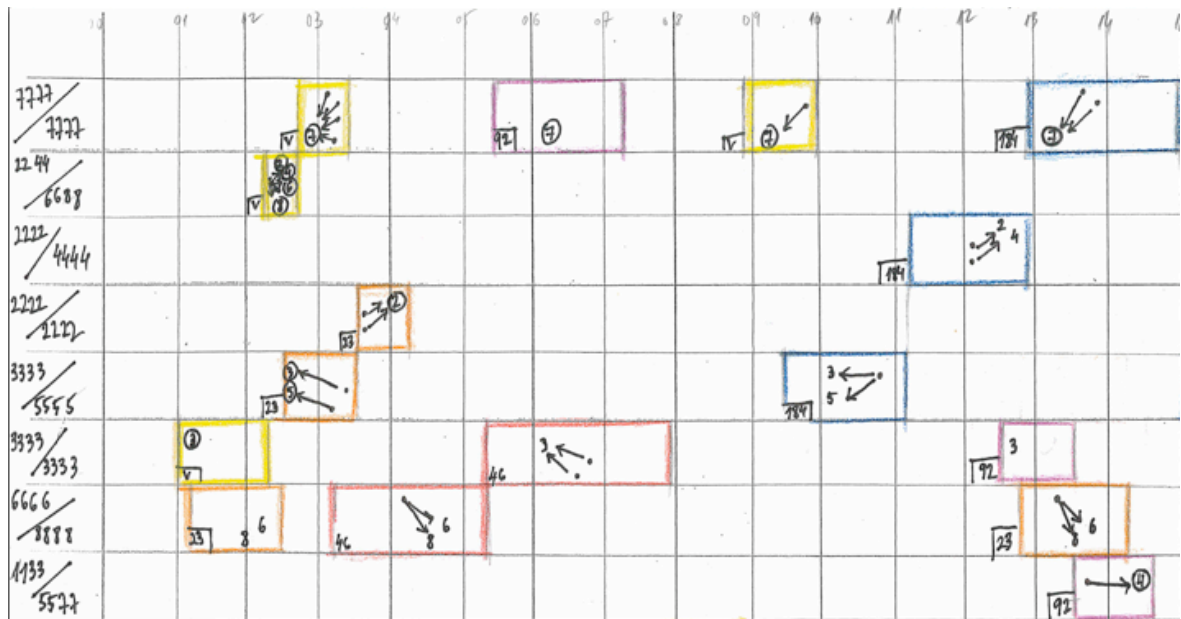


Figure 60. Detail of a polyphonic texture (test 4.4.1, 00'00'' to 00'15'') showing how each texture is molded in space following specific sound-space density variations.

This example corresponds to tests 4.4.1, which experiments with the creation of polyphonic textures. This polyphonic textures consists of five different layers (each represented by a different color), all of which use 8-note groups with the same frequency (53 Hz) but with different note durations as well as relative and absolute positions.¹⁶³ As it can be seen, each texture goes through different sound-space densities using complementary absolute positions, which are specified at the left margin (7777-7777/ 2244-6688/ 2222-4444/ 2222-2222/ 3333-5555/ 3333-3333/ 6666-8888/ 1133-5577/ 4444-

¹⁶³ The exact note durations as well as relative and absolute positions for each layer are described in test 4.4.1 included in the appendix, p.294.

4444/ 2226-6688),¹⁶⁴ so no overlapping between textures in space occur. The number next to each texture corresponds to its note duration (11, 23, 46, 92, and 184 ms), while the arrows and numbers indicate the initial absolute position, i.e. number and position of loudspeaker(s), and the movement to the next one. The duration in ms is specified above.

The complementary absolute positions in figure 56 follow the “principle of no overlapping,” by which one loudspeaker cannot radiate two or more different textures simultaneously. The principle of no overlapping guarantees the maximal spatial differentiation between layers, which is a fundamental condition of sound clarity and transparency (see subchapter 1.1).

3.7 The Importance of Using Sound Location and Sound-Space Density Variations Applied to 8-note Groups: “Source Bonding”

The most important function of space in the compositions presented in this thesis is the possibility to establish a “source bonding”¹⁶⁵ or cause-effect relation between the movement of the 8-note groups through different sound locations and sound-space densities, and the perception of sound attribute and texture variations.

The term “source bonding” is used by D. Smalley to define “the natural tendency to relate sounds to supposed sources and causes, and to relate sounds to each other because they appear to have shared or associated origins”.¹⁶⁶ Smalley states that source bonding disappears with electronic music due to the artificiality implicit in the electronically generated sounds, which prevents their being related to recognizable physical or natural gestures. This is not the case with instrumental music or *musique concrète*. In instrumental music, for instance, source bonding is produced by the physical interaction of the performer with the instrument, as the spectromorphological design of the sound is indicative of how the instrument is excited by the performer.¹⁶⁷ *Musique concrète* uses

¹⁶⁴ See test 4.4 in the appendix.

¹⁶⁵ Smalley, D., 1997, *Spectromorphology: Explaining Sound-Shapes*, Organised Sound, Vol. 2(2), Cambridge University Press, pp. 110.

¹⁶⁶ Ibid., p. 110.

¹⁶⁷ Smalley, D., 2007, *Space-Form and the Acousmatic Image*, Organised Sound, Vol. 12(1), Cambridge University Press, pp. 35-58.

sounds that are recorded from the real world, so it is almost impossible not to recognize them and relate them to their origins.

Smalley considers the possibility to generate sounds detached from their sound sources and physical gestures, which he calls “gestural surrogacy,”¹⁶⁸ as one of the main achievements of electronic music. The “reduced listening” proposed by Pierre Schaeffer in his book *Traité des Objets Musicaux* inspires this approach. Schaeffer pretended to focus the attention on the properties of the sound itself, detached from its extrinsic or referential properties. This type of listening is extremely difficult to achieve, due to the natural tendency to relate any sound to a source and a cause.

However, even though Smalley highlights the advantages of gestural surrogacy in electroacoustic music, he also considers that “music that doesn’t take some account of the cultural embedding of gesture will appear to most listeners a very cold, difficult, even sterile music.”¹⁶⁹

In my opinion, gestural surrogacy is one of the weak points in some electronic music precisely because the natural tendency to the cause-effect relation is not fulfilled.¹⁷⁰ The interest of listening to a piece of music is proportional to the expectations that the musical discourse is able to generate in the listener. The accomplishment or not of what is expected produces different emotional reactions. In this sense, the possibility to relate a particular source or cause to a particular sound, makes it possible to create a dialog between what is expected and what is perceived as a consequence of a particular action, and the following reaction can be analyzed and judged according to a previous expectation.

¹⁶⁸ Smalley defines “gestural surrogacy” as “the process of increasing remoteness (from sources and causes)”, and gives four scales of remoteness (Smalley, 1997, p. 111-112):

- first-order surrogacy refers to sound itself, before it is incorporated to any musical structure or activity,
- second-order surrogacy refers to traditional instrumental gestures with recognizable instrumental skills.
- third-order surrogacy refers to the gesture that is inferred or imagined, with and uncertain cause and/or origin, i.e. the sound quality is unfamiliar or its resonance behaves in an unexpected way, and
- remote surrogacy occurs when the source and cause become unknown and unknowable as any human cause behind the sound disappears

¹⁶⁹ He also says, “the most adventurous extends (of acousmatic music) (are) into third-order ambiguity and beyond to a music which, although remote from traditional sound-making activity, can nevertheless maintain a humanity.” (Ibid., p.112).

¹⁷⁰ Ibid., p.112.

In this case, we consider that the perception of cause-effect relations between sound movement and sound attribute, rhythm, and texture variations contradicts the “gestural surrogacy” attributed to acousmatic music. Even though the sound signals used in the compositions presented in this thesis are electronically generated and thus cannot be related to any original source or cause, the relation between sound movement and the perception of sound attribute, rhythm, and texture variations confers sound gestures and textures a certain “natural” behavior and level of physicality similar to gestures, as they result from the physical movement of sound in space and the psychophysics of human sound localization. In this sense, such cause-effect relations allow electronic sounds to overcome to a certain degree their artificiality.

**Chapter 4. LABORATION OF THE SOUND MATERIAL FOR THE STUDY
OF SOUND ATTRIBUTE, RHYTHM, AND TEXTURE VARIATIONS
AS FUNCTIONS OF SOUND LOCATION AND SOUND-SPACE
DENSITY VARIATIONS.**

**4.1 Relation between the Perception of Sound Attribute Variations Associated
with Spatial Hearing and the Complexity of Sound Signals.**

In order to isolate the effects that sound localization has on the perception of sound attribute variations it is necessary to use time invariant sound signals, i.e. variations in pitch, timbre, or amplitude over time, and sound signals with no complex upper structures (spectra).

Sound attribute variations produced by sound localization are so subtle that they would be completely masked if sound itself were to undergo frequency, amplitude, and timbre variations. Test 1.2.5 shows that when sounds with multiple partials such as triangle waves are used, the perception of sound attribute variations produced by sound position variations, while still perceptible, are highly attenuated. This coincides with the statement that pitch variations produced by variations on sound intensity and duration are less perceptible when using complex sounds (see subchapter 2.5).

In addition, test 1.3 shows that with short note durations of 3 ms, the notes in the 8-note groups are perceived as short impulses (tone bursts). Short impulses present a rich and complex spectrum, and the perception of sound attribute variations produced by varying the sound location is not as clear as with longer note durations.

Therefore, acoustic sounds or complex synthetic sounds are avoided, as the research is limited to the effects that sound localization and sound-space density variations have on the perception of sound attribute, rhythm, and texture variations using signals with an infinite power spectra or energy spectrum such as sine waves, square waves, and triangle waves. All the sound material used in the compositions included in part 2 derive from these sound signals, namely sustained tones, textures, continuums, attacks, gestures, and sound objects. The elaboration of these sound materials is explained in the following subchapters.

4.2 Elaboration of the Sound Material Used in the Compositions Included in Part 2.

As already mentioned in chapter 3, the 8-note groups represent the most elemental formal organization of the sound material presented here. Each 8-note group is defined by a particular type of sound signal, frequency, and note duration as well as relative and absolute distance. These 8-note groups are used to create different types of sound materials, which can be divided into two main groups:

- 1) gestural, which comprises attacks and sound objects, and
- 2) textural, which includes sustained tones, continuums, and textures.

Sustained tones, continuums, and textures use an unlimited number of successive 8-note groups, while attacks, gestures, and sound objects use a limited number of them.

In the particular case of the sustained tones, all parameters except the relative position remain invariable, i.e. sound signal, frequency, note duration, relative and absolute distances, and absolute position. Therefore, only pitch, loudness, and tone color variations are perceived, as only relative position variations occur. The sustained tones also use notes without fade-in and fade-out envelopes, which imply two completely different sound qualities, as each note is perceived with or without a transient sound at the beginning and end of each note. These two sound qualities are more or less important depending on the amplitude, frequency, and note duration of the 8-note groups. In all cases, however, they help to achieve more dynamism when used, for instance, during the same sustained tone, as occurs in the piece *Musical Situation 1*.

When the successive 8-note groups are played through different relative and absolute positions, rhythm and texture variations are also perceived in addition to pitch, loudness, and tone color variations. This is the case of continuums, textures, attacks, gestures, and sound objects.

Textures and continuums are characterized by using short note durations together with relative and absolute distances larger than 0 ms. Continuums represent the most homogeneous textures possible, as they maintain the same sound signal, frequency, note

duration, and invariable relative and absolute distances, while varying the relative and absolute positions. Therefore, the only parameters that provide dynamism to the 8-note groups are the movement of the notes in the 8-note groups in space and the perception of sound attribute, rhythm, and texture variations derived from such movement. Continuums are used in the piece *Polyphonic Continuum*.

The difference between textures and continuums is that the first present variable relative and absolute distances as well as the combination of notes with and without fade-in and fade-out envelopes. These textures are used to create polyphonic textures, double polyphonic textures, and sound objects. Polyphonic textures and sound objects consist of the contrapuntal use of textures with the same frequency but different note durations and relative and absolute distances. The main difference between them is that the duration of the sound objects is very short compared to the polyphonic textures. The double polyphonic textures consist of the contrapuntal use of the previous polyphonic textures, each one with a different frequency. The attacks consist of 5-note groups with different frequencies, note durations, and relative distances. Gestures consist of the successive repetition of the same attack (5-note group) through different absolute positions and with little or no absolute distance. The absolute distance is different for each gesture, and is determined in relation to the note duration and relative distance. Gestures are used in the piece *Topos*, where the number of repeated attacks oscillates between two (00'17'' and 00'24) and twelve (00'01'') (see figure 78, p. 173).

All these sound materials are explained in detail in the following subchapters, and are evaluated according to the perception of sound attribute, rhythm, and texture variations produced by sound localization and sound-space density variations.

4.2.1 The Elaboration of Sustained Tones

A continuous sustained tone consists of an unlimited number of successive 8-note groups with the same frequency and note duration, using both relative and absolute distances of 0 ms. The notes in the 8-note groups are spread in space through the (O) relative position rows, while the absolute position (1234-5678) and sound-space density (8/8) remain invariable.

As frequency, note duration, relative and absolute distances, absolute position, and sound-space density are always the same, the only parameter that undergoes variations is the relative position. In this case, dynamism is achieved by moving the notes in the 8-note groups in space and the perception of pitch, loudness, and tone color variations that occur together with sound movement. Sometimes, the movement of the notes in the 8-note groups in space creates recognizable sound trajectories, which occur mostly when the fade-in and fade-out envelopes are removed and the transient sounds at the beginning and end of each note are perceived.

In relation to the perception of pitch, loudness, and tone color variations, experiment 2 proves that sustained tones are perceived with more or fewer sound attribute variations depending on the frequency and note duration of the notes in the 8-note groups. Regarding pitch perception, it is necessary that each note in the 8-note group contain a certain number of cycles in order to perceive the pitch clearly (see subchapter 2.5), which varies depending on each frequency. Test 2.1 confirms Moore's model of pitch perception¹⁷¹ (see figure 32, p. 92) by presenting a 408 Hz sustained tone whose note duration dilates from 1ms to 226 ms. Around 40 ms the pitch is totally well-perceived, which implies twelve cycles. From 1 to 33 ms, the 408 Hz sine waves are perceived as a mixture of pitched and non-pitched.¹⁷²

As soon as pitch perception of the individual notes in the 8-note group is well-defined, the notes in the 8-note groups that participate in the sustained tone are perceived with important pitch, loudness, and tone color variations. This is the case of a 53 Hz sustained tone with note duration of 386 ms, or a 159 Hz sustained tone with note duration of 180 ms, both used in *Musical Situation 1*. In these cases, even though the same amplitude is assigned to each note in the 8-note group, some notes are perceived much louder than the others, creating the perception of an internal rhythm. This phenomenon may occur due to the constructive and destructive interferences created by the primary sounds and early reflections (see subchapter 2.7), as well as the variations in sound pressure created by the different angle of incidence to the ears of each note in the 8-note group (see subchapter 2.2 and 2.4).

¹⁷¹ Moore's model indicates that higher tones need more cycles compared to lower tones.

¹⁷² Schaeffer's *Traité des objets musicaux* (1966) presents important studies showing the dependence of amplitude and duration on the perception of timbre, which represents the color of any pitch. In 1967 these studies were accompanied by audio examples, which can be found in 3 CDs entitled *Solfège de l'objet sonore*.

In addition, test 2.1.7 shows that in the case of a 318 Hz sustained tone with a note duration of 46 ms (14 cycles), it is not possible to differentiate each note in the 8-note groups individually, and only a diffuse sound field is perceived. As already mentioned in subchapter 2.7, diffuse sound fields can occur by dividing a tone into small units and spreading them in space through multiple sound sources. As it is not possible to differentiate each note in the 8-note groups, it is not possible to perceive sound attribute variations between them.

However, the perception of diffuse sound fields is crucial to create spatial depth and sound relief, especially when they appear together with other sustained tones using notes without fade-in and fade-out envelopes, as occurs several times in *Musical Situation 1* (for instance between 01'00" and 01'30"). This piece uses several sustained tones with different frequencies and note durations. In each particular case, either pitch, loudness, and tone color variations of the notes in the 8-note groups are clearly perceived or they create diffuse sound fields. This composition is explained in detail in subchapter 5.3.

4.2.2 The Elaboration of Textures.

The perception of sound textures occurs when the 8-note groups use short note durations (ca. 30 ms) and relative and absolute distances larger than 0 ms. The temporal and spatial organization of the 8-note groups defines the quality of such textures, which are different depending on

- 1) the note duration,
- 2) the relative and absolute distances, and
- 3) the relative and absolute positions.

First, note duration determines the perception of more or less pitched or non-pitched notes in the 8-note groups. Second, the relative and absolute distances determine the temporal density of the 8-note groups by assigning a particular distance between the notes in the 8-note groups as well as the distance between successive 8-note groups. Third, the relative and absolute positions determine the position and the amount of space, i.e. sound-space density, between the notes in the 8-note groups.

In order to investigate how these parameters influence the perception of sound attribute, rhythm, and texture variations as well as sound localization, experiment 4 uses successive 8-note groups with different sound signals, frequencies, note durations, relative and absolute distances, and relative and absolute positions. To avoid the perception of recognizable sound trajectories as well as repeated rhythmic patterns, the 8-note groups are played successively through the (O), (R), (I), and (RI) relative position rows (see figure 48, p. 119).

Test 4.1.1, for instance, proves that playing successive 8-note groups through the (O), (R), (I), and (RI) relative position rows while maintaining the same absolute position, the resulting textures are not dynamic enough, as the perception of sound attribute, rhythm, and sound location variations are too subtle.

On the contrary, enough dynamism is achieved when the relative position rows are played together with absolute position variations, as rhythm and texture variations are also perceived in addition to pitch, loudness, tone color, and sound localization variations. Therefore, it can be stated that relative and absolute position variations create dynamic textures.

4.2.2.1 The Creation of Long Dynamic Homogeneous Textures: Continuums

Test 4.2 undertakes further experiments to evaluate to which extent simultaneous relative and absolute position variations are able to create long dynamic homogeneous textures. These long textures are referred to here as "continuums", and consist of regular, uniform, and stable textures in time that exhibit an internal dynamism when submitted to sound location and sound-space density variations. In this case, dynamism refers to the movement of sounds in space, which is perceived together with pitch, loudness, tone color, rhythm, and texture variations.

In relation to the sound material, test 4.2 shows that textures can present various levels of dynamism independently of their movement in space, using variable or invariable relative and absolute distances. In this sense, three levels of dynamism can be achieved by using successive 8-note groups with

- 1) invariable relative and absolute distances, which represent the least dynamic

- sound material (test 4.2.3, 4.2.4, 4.2.5),
- 2) invariable relative distances but variable absolute distances (test 4.2.2), and variable relative and absolute distances, which represent the most dynamic sound material (test 4.2.1).

In any case, all these combinations proved to be equally valid in relation to the perception of sound attribute, rhythm, and texture variations.

To achieve continuous and at the same time "dynamic" homogeneous textures (continuums), it is necessary that the notes in the 8-note groups constantly change position, by playing them continuously through relative and absolute position and sound-space density variations. In order to create long continuums and to avoid the perception of repeated rhythmic patterns or recognizable sound trajectories, which occur when the same relative and absolute position rows are repeated one after the other, the 8-note groups must follow four successive steps:

- 1) The eight notes in the 8-note groups are organized following the (O), (R), (I), and (RI) relative position rows (see figure 48, p. 119).
- 2) The resulting 8-note groups are played continuously through 12 absolute position rows, resulting the first short continuum.
- 3) The short continuum is then repeated again through its retrograde, inversion, and inversion of the retrograde. The resulting continuum will be the original version of the long continuum.
- 4) In order to create an even longer continuum, the original version of the long continuum is repeated through its retrograde.
- 5) Finally, the continuum resulting from the sum of the original and retrograde versions is repeated in a loop.

Test 4.2.3 shows that using 8-note groups with a frequency of 318 Hz, note duration of 46 ms, and relative and absolute distances of 16 ms, creates a regular, stable, and uniform sound continuum. The notes in the 8-note groups are perceived as individual sound impulses, more pitched than non-pitched, resulting a continuum with a mildly rough sound quality. In this sense pitch, loudness, and tone color variations, as well as sound

location and sound-space density variations are well-perceived.

On the contrary, the texture of a 795 Hz 8-note group with note durations of 8 ms (see test 4.2.5) presents a sharper, rough character, as with this note duration the sound quality is a mixture of pitched and non-pitched. In this case, sound localization becomes more important than sound attribute, rhythm, and texture variations.

By comparing test 4.2.3 with test 4.2.1, it is evident that more dynamism is achieved when using variable relative and absolute distances, as, together with sound-space density variations, additional textural variations are produced by variable levels of temporal sound density.¹⁷³

In order to evaluate the real influence of sound spatialization on the perception of sound attribute, rhythm, and texture variations, the temporal variations involved in the 8-note groups used to form the textures should be as static as possible.

Test 4.3 proves that as soon as the initial frequency, note duration and relative and absolute positions cease to change in the course of the same texture, relative and absolute position variations are enough to create important variations in the perception of pitch, loudness, tone color, rhythm, texture, and sound localization variations.

The most important characteristic of these static textures is that it is possible to perceive clearly the dialog between sound movement and sound perception, i.e. the cause-effect relations between sound localization, sound-space density variations, and the perception of sound attribute and texture variations, which prove to be so important in the creation of longer compositions such as *Polyphonic Continuum*.

4.2.2.2 The Creation of Polyphonic Textures with the Same Frequency Using Sound-Space Density Variations and the Principle of No Overlapping

Test 4.4 experiments with polyphonic textures with the same frequency used in test

¹⁷³ Temporal sound density refers here to the number of notes in the 8-note groups per time unit, which is determined by the relative and absolute distance. As already mentioned, the number of notes per unit space is determined by the sound-space density. Differences in spatial and temporal sound densities have direct consequences on the quality of sound, as the 8-note groups are perceived with different levels of textural roughness or smoothness.

4.3. The purpose of this test is to experience to what extent the dialog between sound movement and sound perception is still perceptible or is masked by the complexity of the polyphonic structure.

As the textures used in each of the polyphonic textures have the same frequency and note duration, they are only differentiated by different relative and absolute distances. Therefore, in order to guarantee the maximal differentiation between textures, the polyphonic texture respects the principle of no overlapping, so the same loudspeakers cannot radiate more than one texture at the same time. At the same time, each texture is spread in space using contiguous sound sources only, which implies that each texture is not fragmented but limited to a specific area in space (see figure 46, p. 115). For instance, following the octagonal position and numerical order of the eight sound sources indicated in figure 19 (p. 69), contiguous sound sources are 2-4-6 or 5-7-8-6.

To evaluate the importance of sound spatialization and the principle of no overlapping to the perception of sound clarity and transparency, the corresponding audio files¹⁷⁴ of tests 4.4 present each polyphonic texture two times, one using sound-space density 8/1 (sound source 1) and another using sound-space density 8/8. In general, using sound-space density 8/1, different textures are indeed perceived. However, as soon as the texture with the shortest relative distance is louder than the others, the textures with longer relative distances are completely masked. On the contrary, using sound-space density 8/8, more textures are perceived compared to sound density 8/1. Consequently, more sound transparency is achieved using sound spatialization together with the principle of no overlapping.

Each polyphonic texture consists of five textures, although not all textures are played simultaneously. In contrast to the continuums, where each texture is played with no interruption from beginning to end, each texture involved in the polyphony goes through two or three different absolute positions before it disappears. The following figures 61, 62, and 63 corresponding to tests 4.4.1, 4.4.2, and 4.4.3 are graphic representations of the movement of six polyphonic textures.¹⁷⁵

¹⁷⁴ The audio files corresponding to each test can be found in the DVDs included in appendix III. Each DVD contains Pro Tools sessions with the audio files corresponding to each test.

¹⁷⁵ The graphic representations of tests 4.4.4, 4.4.5, and 4.4.6 are included in appendix II.

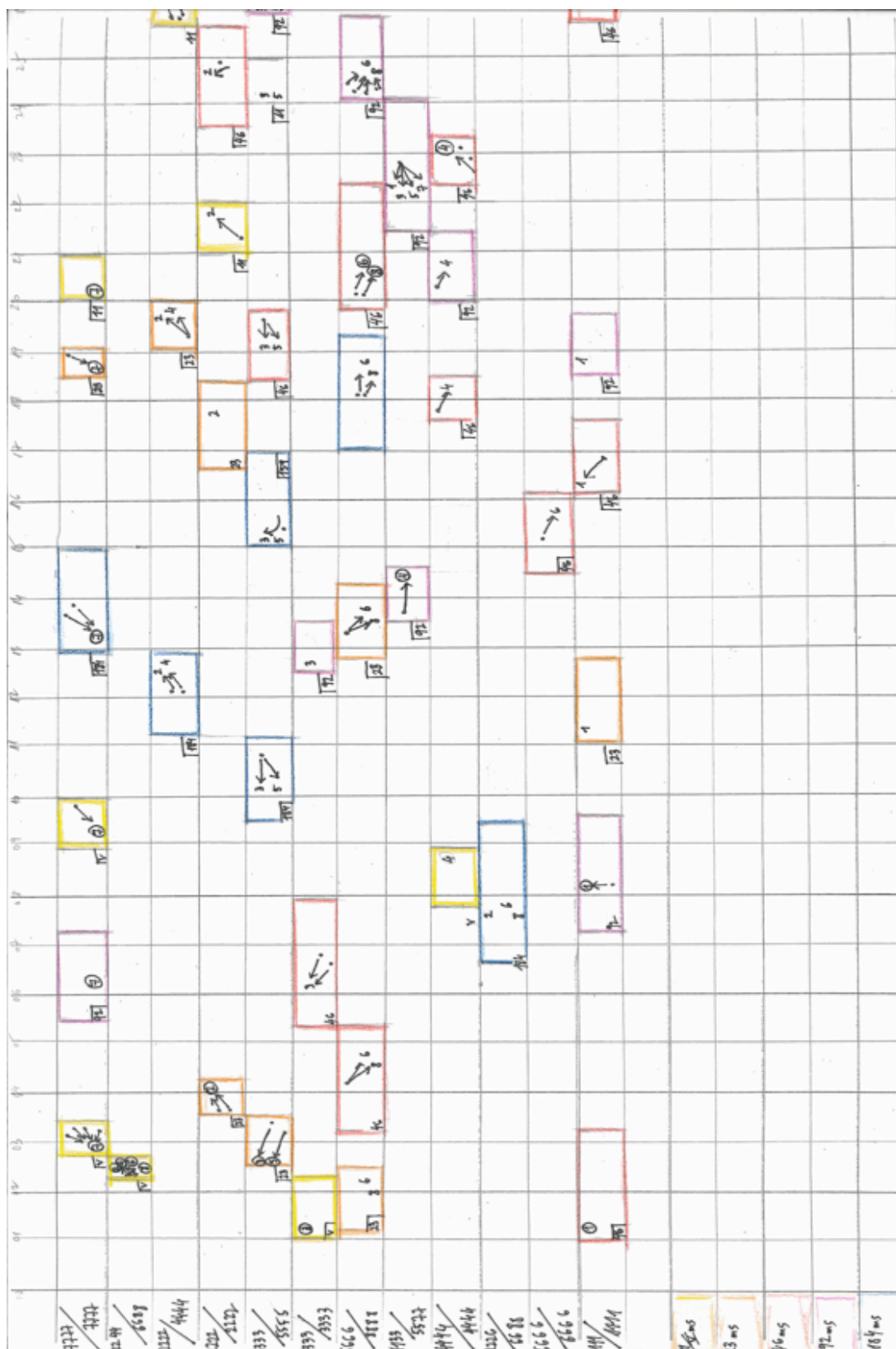


Figure 61. Polyphonic texture corresponding to test 4.4.1

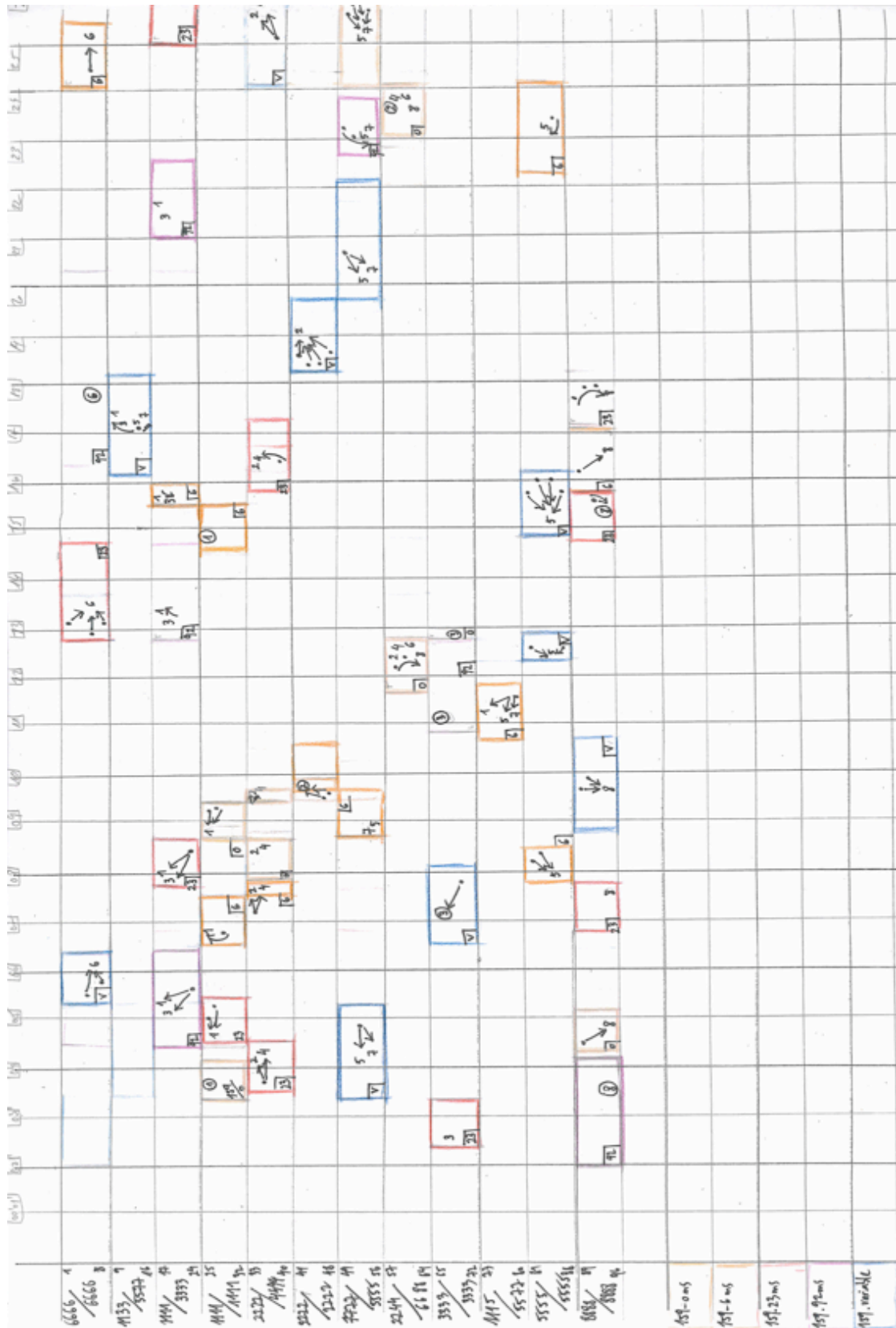


Figure 62. Polyphonic texture corresponding to test 4.4.2.

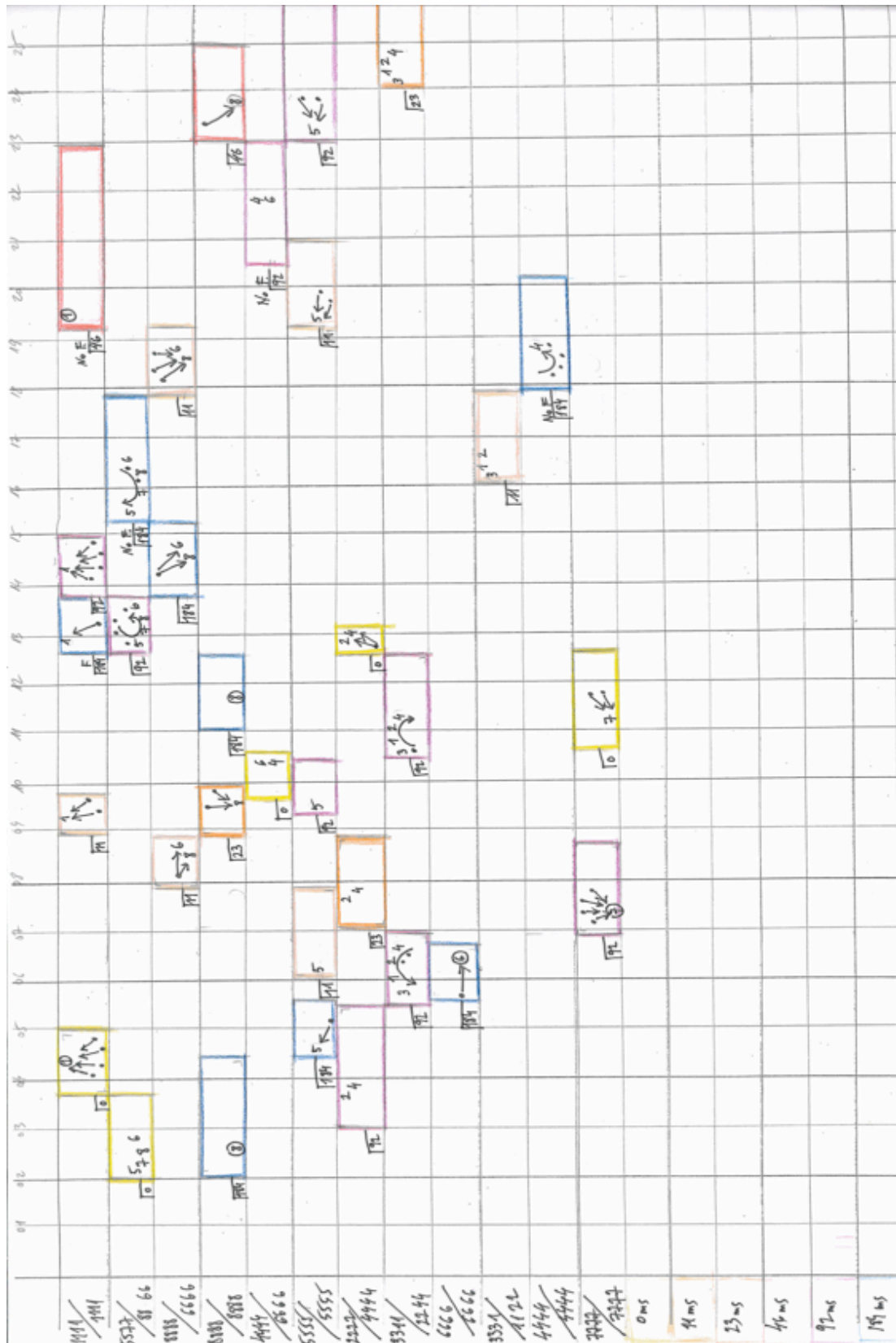


Figure 63. Polyphonic texture corresponding to test 4.4.3.

However, even when using sound-space density 8/8 it is difficult to isolate each layer from the others and perceive the sound attribute, rhythm, and texture variations that occur together with sound localization and sound-space density variations. The main reason why the expected cause-effect relations are not perceived may be

- 1) the textures are too similar one another. Certainly, they use the same frequency and note durations, and only the relative and absolute distances are different. Consequently, the polyphonic texture is perceived as one unique texture going through different levels of sound density produced by the variable relative and absolute distances. Other variations produced by sound movement and sound-space density variations are completely masked,
- 2) each layer appears at different moments, changes its absolute position 3 or 4 times only, and disappears. Due to the speed of the spatial movement and the short duration of each texture, it is not possible to identify and isolate each individual texture and follow its spatial movement. As textures are not clearly differentiated one another, the listening can not establish a direct relation between sound movement and sound attribute and texture variations.

Test 4.4 shows that as soon as the dialog between space and sound perception is no longer perceived, the polyphonic textures cease to be interesting, as they are perceived as monotonous and repetitive. Consequently, these polyphonic textures are not used in any of the compositions included in part 2.

4.2.2.3 Elaboration of Double Polyphonic Textures

Test 4.5 tries to solve some of the problematic issues that appeared in tests 4.4 by playing some of the previous polyphonic textures simultaneously, creating double polyphonic textures (see figures 64 and 65). The main differences in relation to tests 4.4 are that:

- 1) the duration of each polyphonic texture is longer, which permits the listening to

- better perceive the spatial movements of each texture,
- 2) each polyphonic texture uses a different frequency, which permits the listener to differentiate each polyphonic texture more easily , and
 - 3) the perception of monotonous and repetitive polyphonic textures in test 4.4 is avoided here by using more frequencies and note durations, as well as creating the possibility to identify and follow their movement in space.

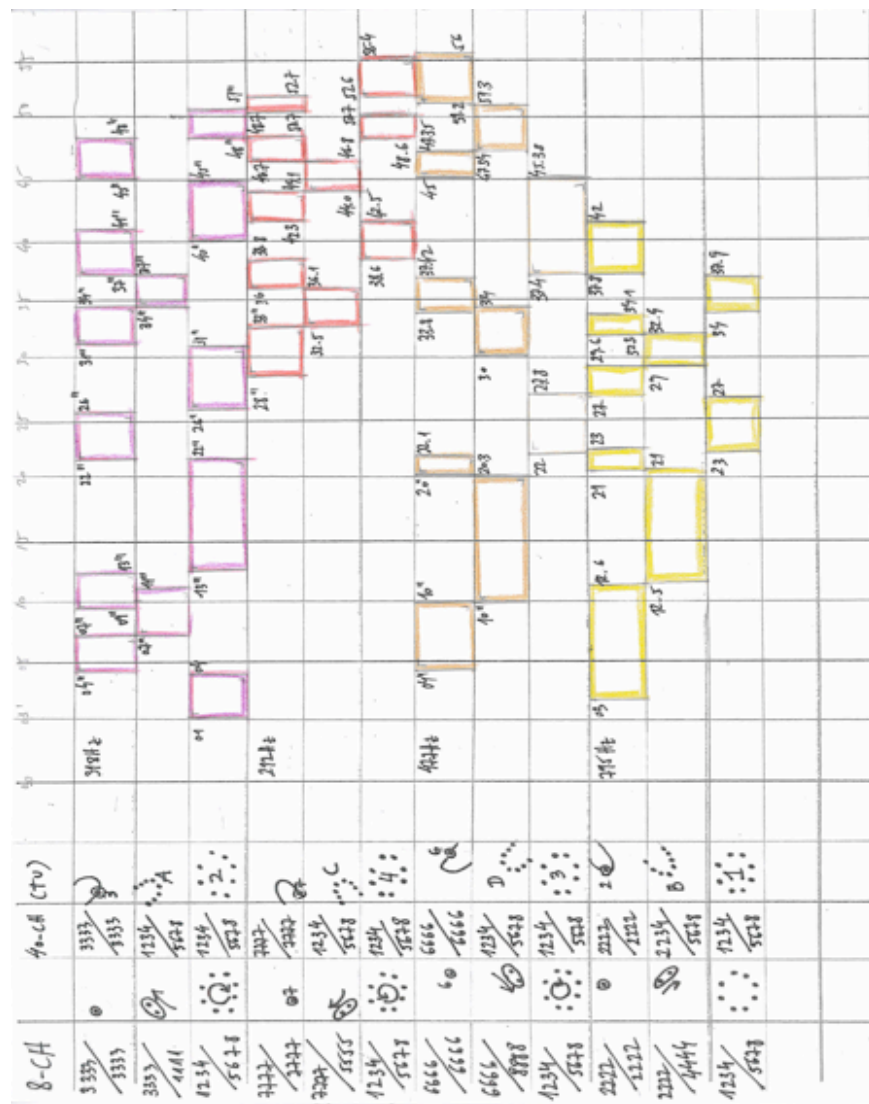


Figure 64. Double polyphonic texture using four polyphonic textures with frequencies of 212, 318, 477, and 795 Hz.

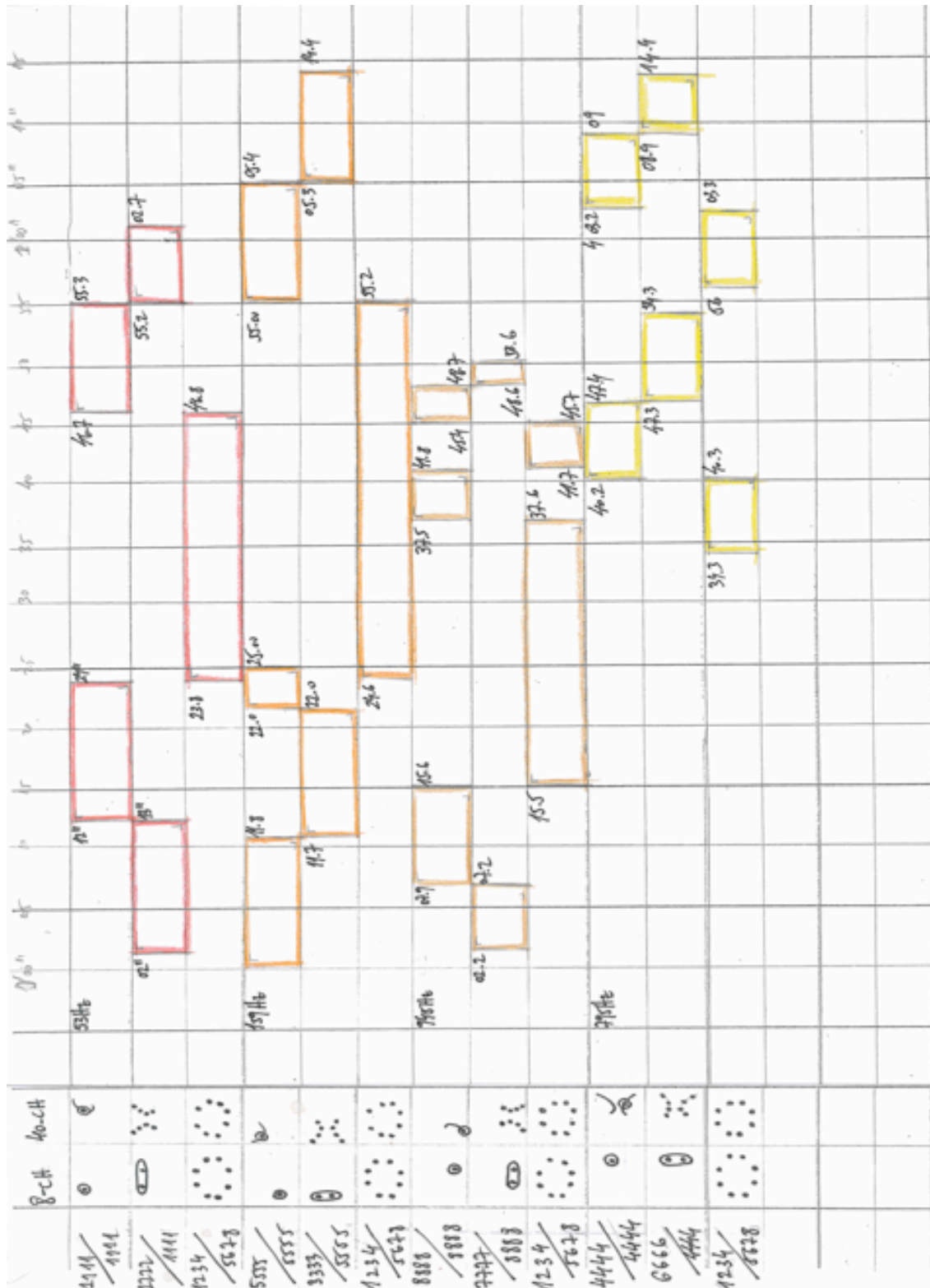


Figure 65. Double polyphonic texture using four polyphonic textures with frequencies of 53, 159, 795, and 954 Hz.

The most important objectives in test 4.5 are to discern

- 1) if it is possible to perceive the dialog between sound attribute and texture variations and the movement of sound through different sound locations and sound-space densities, and
- 2) at the same time if it is possible to create a dynamic musical situation using simultaneous polyphonic textures with different frequencies without the need to perceive such a dialog.

Each double polyphonic texture uses four of the previous polyphonic textures with the following frequencies: (1) 212, 318, 477 and 795 Hz, and (2) 53, 159, 795 and 954 Hz. Throughout the double polyphonic texture, each polyphonic texture expands and contracts its spatial extension using sound-space densities $8/1$, $8/2$, and $8/8$. In order to better differentiate each polyphonic texture, at the beginning they occupy a different aural hemisphere, which is specified at the left margin, and only after a certain time they are spread in space using the only circle available, as only a total of eight sound sources are used.

Test 4.5 shows that with different frequencies, the listener can easily identify each polyphonic texture and follow its spatial movement, even when all of them occupy the same circle and the principle of no overlapping cannot be fulfilled. However, the dialog between sound attribute, rhythm, and texture variations and the movement of sound through different sound locations and sound-space densities is again not perceived, as it is completely masked by the variations that occur in time, i.e. the perception of sound attribute, rhythm, and texture variations produced by relative and absolute distance variations.

Consequently, the double polyphony is perceived as a regular four-texture polyphony, where each polyphonic texture is perceived as the mutation of the same texture through different sound densities produced by variations on the relative and absolute distances.

Although both double polyphonies presented here are much more dynamic than the

previous polyphonic texture, they are not dynamic enough to create an interesting musical situation. The main reason is that, as occurred with the polyphonic textures, sound attribute and texture variations are not perceived as being related to sound movement and sound-space density variations. The dialog between space and sound disappears, and the listener perceives many variations with no relation to spatial movement. The listening is then limited to the contemplation, or better said auscultation, of a texture whose internal activity happens for no apparent reason. In addition, sine waves and triangle waves are not dynamic sound signals, as they contain no pitch, amplitude, or timbre variations over time.

From test 4.5 it can be deduced that only by using textures with the same frequency, note duration, and relative and absolute distances, as in the case of continuums, the perception of sound attribute, rhythm, and texture variations emerge, and the listener can associate them with the movement of sound through different sound locations and sound-space densities. Only then the dialog between sound spatialization and sound perception is achieved.

The perception of sound movement associated with pitch, loudness, tone color, rhythm, and texture variations occurs when using continuums, and this dialog between sound movement and sound perception enriches the listening experience. Ironically, more dynamism is achieved by using more static textures, which may seem to contradict the previous statement that more variations in the sound parameters are needed in order to achieve a more dynamic and interesting texture.

Therefore, the continuums presented in test 4.2 and 4.3 seem to be the most convenient to create a polyphonic texture, and they are used to create the piece *Polyphonic Continuum* included in part 2. In this composition, each continuum has a different frequency, so they are more differentiated. At the same time, each continuum is played with no interruption for long periods of time, so the listener has no difficulty to identify each continuum, follow its spatial movement, perceive its different sound locations and sound-space densities, and relate the variations in the perception of sound attributes, rhythm, and textures to the movement of sound in space. This composition is explained in subchapter 5.2.

4.2.3 The Elaboration of 5-note Group Attacks and Short Gestures

Test 1.5 shows that when using individual 8-note groups with short note durations, the perception of sound attribute variations is almost inexistent and, consequently, the listener focuses on sound localization. In order to perceive more sound attribute variations between the notes in the note groups, instead of 8-note groups with the same frequency and relative distance, test 3.1 uses 5-note groups with different frequencies as well as different relative distances.¹⁷⁶ Each 5-note group uses five of the following seven frequencies: 159, 53, 212, 318, 477, 795, and 954 Hz. Both the frequencies of each 5-note group as well as their chronological order are determined by eight frequency rows specified in figure 66.

1. 159 / 53 / 212 / 318 / 477	5. 477 / 795 / 954 / 159 / 53
2. 53 / 212 / 318 / 477 / 795	6. 795 / 954 / 159 / 318 / 212
3. 212 / 318 / 477 / 795 / 954	7. 954 / 159 / 53 / 212 / 318
4. 318 / 477 / 795 / 954 / 159	8. 159 / 795 / 212 / 318 / 477

Figure 66. Frequency rows used for the 5-note groups used in test 3.1.¹⁷⁷

In order to experiment with how different the perception of sound attribute and sound localization variations are when using different relative and absolute positions, the notes in the 5-note groups in test 3.1 are played through the (O) relative position rows only or through simultaneous relative and absolute position variations. In addition, each individual test uses different note durations and relative distances, which are indicated in figure 67.

¹⁷⁶ In test 1.5, the relative distance for all 8-note groups is always 0 ms.

¹⁷⁷ These rows are designed to follow a spiral movement to the left following the frequency order 159, 53, 212, 318, 477, 795, 954 Hz. The first frequency of the row disappears and the second takes its place, while a new frequency appears at the right. The reason for this system is that the tests show that with attacks with short note durations, the first and last notes are more important than the middle ones. Therefore, the spiral movement always changes the first and last notes while keeping the middle ones. The numbers that are in bold (rows 6 and 8) indicate that the normal spiral movement is not followed, and another frequency is used. The reason for these changes are that as soon the attacks use longer note durations, the middle notes become more audible, and it was noticed that the same frequencies remained almost identical for successive attacks. Therefore, two new frequencies are used to increase variation between attacks.

1 ms 5-note-groups		6 ms. 5-note-groups		11 ms. 5-note-groups	
1.	0 ms	1.	0, 0, 0, 0 ms	1.	11, 0, 3, 6 ms
2.	1, 2, 3, 1 ms	2.	3, 6, 1, 3 ms	2.	23, 11, 6, 11 ms
3.	6, 3, 1, 6 ms	3.	11, 6, 3, 11 ms	3.	0, 0, 0, 0 ms
4.	11, 6, 3, 11 ms	4.	11, 6, 6, 23 ms	4.	3, 11, 23, 23 ms
5.	11, 6, 23, 3 ms	5.	3, 6, 3, 11 ms	5.	6, 0, 3, 23 ms
6.	23, 11, 11, 46 ms	6.	11, 11, 23, 11 ms	6.	23, 23, 11, 11 ms
7.	11, 6, 23, 46 ms	7.	6, 23, 3, 11 ms	7.	23, 46, 11, 46 ms
8.	46, 11, 23, 46 ms	8.	11, 23, 46, 11 ms	8.	11, 6, 23, 3 ms

23 ms. 5-note-groups		46 ms. 5-note-groups	
1.	23, 0, 0, 23 ms	1.	23, 0, 46, 11 ms
2.	23, 11, 23, 46 ms	2.	46, 0, 46, 46 ms
3.	0, 0, 0, 0 ms	3.	46, 0, 0, 92 ms
4.	0, 11, 23, 6 ms	4.	46, 92, 0, 0 ms
5.	0, 23, 23, 46 ms	5.	0, 0, 46, 92 ms
6.	23, 23, 0, 23 ms	6.	0, 0, 0, 0 ms
7.	46, 0, 11, 23 ms	7.	23, 6, 11, 6 ms
8.	0, 0, 46, 11 ms	8.	0, 23, 11, 92 ms

Figure 67. Relation of note durations and relative distances for the 5-note groups used in test 3.1.

Following the results of test 3.1, it can be stated the perception of pitch, loudness, and tone color variations derived from sound localization are completely masked as soon as each note in the 5-note groups has a different frequency, using relative positions only or simultaneous relative and absolute position variations. Only sound location variations are clearly perceived, although with no consequences for the perception of sound attribute variations.

In addition, using different frequencies for each note in the 5-note groups decreases the perception of sound location variations, so relative position variations become less important than for 8-note groups with the same frequency as in experiment 1. Even using simultaneous relative and absolute position variations, frequency variations are so important for the listening that like pitch, loudness, and tone color variations, sound location variations become are distinguished.¹⁷⁸

¹⁷⁸ This assertion concurs with Boulez's statement that pitch and duration are the most important parameters in music, followed by rhythm and amplitude. That means that the listener pays more attention to pitch and rhythm, followed by timbre and amplitude. (Boulez, P., 1966, "... *Auprès et au loin*", Cahiers, Paris, p. 7-24, and Boulez, P., 1963, *Penser la musique aujourd'hui*, Editions Gonthier, Paris, p. 37-38). The experiments undertaken in this thesis show that sound spatialization would be the least important of all of them.

Moreover, successive 5-note group attacks are perceived as repetitive and monotonous because they are based on the same seven frequencies. In order to achieve a dynamic situation using 5-note groups with different frequencies, it would be necessary that the 5-note groups use different frequencies continuously. This possibility is not explored here because it is not related to this research, which is dedicated to investigating the perception of sound attribute variations derived from sound location and sound-space density variations.

Therefore, it can be stated that frequency variations capture the attention of the listener to such an extent that the perception of other sound attributes, i.e. pitch, loudness, tone color, and sound movement variations, diminishes. These results show that in order to perceive sound attribute, rhythm, texture, and sound location variations produced by sound location and sound-space density variations, it is necessary that sound is as static in time as possible, which requires that the notes in the note groups use the same frequency.

4.2.3.1 Using the “Right-Left Sound-Space Dilation Rows” to Mold Successive 5-Note Group in Space: Sound Transparency and Sound Directionality

Test 3.1 shows that pitch, loudness, tone color, and sound location variations become highly masked when using note groups with different frequencies. At the same time, it demonstrates that with the use of a limited number of frequencies,¹⁷⁹ the perception of successive individual 5-note groups is repetitive and monotonous, no matter how dynamic sound location and sound-space density variations may be. This is especially true when the notes in the 5-note groups are perceived as more pitched than non-pitched.

Test 3.2 is a further attempt to achieve more dynamism by incorporating “sound gestures,” which are created by playing successive 5-note groups with little or no absolute distance between them through very differentiated sound locations and sound-space densities. The gestures introduced in this thesis can be described following the definition proposed by Smalley, who considers sound gestures as trajectories of energy and motion that create a spectromorphological life.¹⁸⁰ This is achieved using the so-called “right-left

¹⁷⁹ As before, the 5-note groups use a different combination of the same seven frequencies.

¹⁸⁰ Smalley, 1997, p. 111.

sound-space dilation rows” shown in figure 68, which create a spatial dilation of 5-note groups by alternating the left and right aural hemispheres, so they are spatially more differentiated from one another. In addition, the right-left sound-space dilation rows supply each 5-note group with a spatial directionality, which contributes to spatially shaping individual or successive 5-note groups.

1.	1234-5678	8/8
2.	7777-7777	8/1
3.	7864-2211	8/6
4.	7755-5333	8/4
5.	7788-8666	8/3
6.	7531-1244	8/6
7.	7788-6644	8/4
8.	7755-3311	8/4
9.	7866-4422	8/5
10.	7533-1122	8/5
11.	7777-8888	8/2
12.	7777-5555	8/2

Figure 68. Right-left sound-space dilation rows.

As it can be seen, the right-left sound-space dilation rows also differentiate the 5-note groups by using a different number of sound sources, so the notes in the 5-note groups are more or less extended in space. Besides the right-left sound-space dilation rows, the exact position of each note in the 5-note group is determined by the first five positions of the (O) relative position rows (see figure 40, p. 105).

Test 3.2 uses the same 5-note groups used in test 3.1, i.e. with the same frequencies, relative and absolute distances, and relative positions. However in tests 3.2 each note group is presented three times:

- 1) the initial 5-note group attacks are presented in sound source 7,
- 2) the same 5-note group is repeated with the same sound-space density 5/1 but in another sound source (1, 2, 3, 4, 5, 6, or 8), thus changing their sound location, and

- 3) the same 5-note group is repeated one or more times following the left-right sound-space dilation rows (see figure 69).

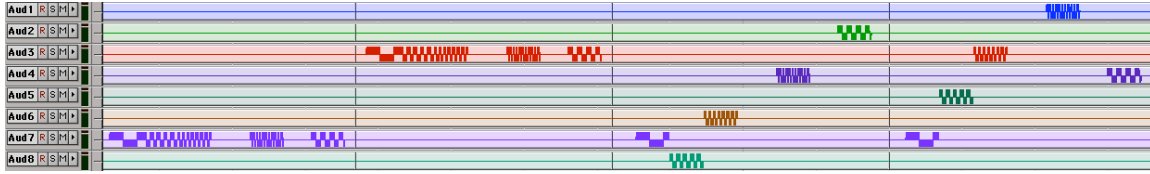


Figure 69. Graph of the right-left sound-space dilation rows using 5-note groups.¹⁸¹

Taking into consideration that the perception of sound attribute and sound location variations are highly diminished by the use a different frequency for each note in the 5-note groups, test 3.2 uses amplitude variations (see figure 70), so some 5-note group are more audible than others.

1.	Track 1-8	0 dB	7.	Track 49-56	-6 dB
2.	Track 9-16	0 dB	8.	Track 57-64	0 dB
3.	Track 17-24	-3 dB	9.	Track 65-72	-3 dB
4.	Track 25-32	-9 dB	10.	Track 73-80	+6 dB
5.	Track 33-40	-6 dB	11.	Track 81-88	0 dB
6.	Track 41-48	+3 dB	12.	Track 89-96	-3 dB

Figure 70. Amplitude variations between the 5-note groups used in test 3.2.

Together with the sound directionality and sound transparency achieved with the right-left sound-space dilation row, amplitude variations contribute as well to mold particular shapes to each sound gesture, as the individual notes in the 5-note groups are perceived at different distances in relation to one another.

It is important to mention that even using sound-space density 5/1, i.e. with no spatialization, the notes in the 5-note groups are perceived as spatialized both in the horizontal and the vertical planes. On one hand, the “inner” listening separates each note

¹⁸¹ This example follows sound-space dilation rows three and six. Note that only the first five positions of the rows are used, as, differently to the 8-note groups, the note groups have only five notes.

spatially due to the cross-correlation processes that occur at the auditory system, which take into consideration the degree of coherence (k) between two sound signals. Basically, due to the dependence of interaural time and phase delays on frequency, the auditory system separates the components of different frequencies, displacing them laterally by different amounts, and creating the effect that the auditory event has spread out (see subchapters 2.2 and 2.3).

At the same time, there is a metaphorical space associated with the lower and higher frequencies. Lower frequencies, for instance, tend to be metaphorically or mentally located “below”, and high frequencies “above.” As Trevor Wishart says,

Musicians have always implicitly accepted some kind of metaphorical or analogical link between perceived pitch and height. We speak about “high” pitches and “low” pitches (...) it is fairly easy to hold to this metaphor when one is dealing with a set of sounds of fixed timbre. (...) Whatever is the explanation of that musical phenomenon, composers of instrumental music often exploited the spatial metaphor or analogy. For example, the open textures of some of Sibelius' orchestral writing where a low bass line moves against a high melody with little or nothing in the intervening space generates a sense of a vast and empty landscape.¹⁸²

We want to conclude saying that the particularity of the gestures introduced in this thesis lie in that the movement of sound in space is integrated, perhaps for the first time, as part of its spectromorphological profile. That is, the spectra of the sound object and its morphological variations, at least concerning sound perception, are a direct and exclusive consequence of sound movement and not of any synthetic manipulation of sound.

4.2.4 The Elaboration of Sound Objects.

The previous tests 4.2 and 4.3 show how relative and absolute position variations confer dynamism to continuums, which are textures that use 8-note groups with the same frequency, note duration, and relative and absolute distances. Instead of creating long continuums, test 5.1 uses the same textures to create sound objects (see figures 71 and

¹⁸² Wishart, Trevor, 1996, *On Sonic Art* (new revised edition, Emmerson, ed.). New York: Routledge, pp. 109-110.

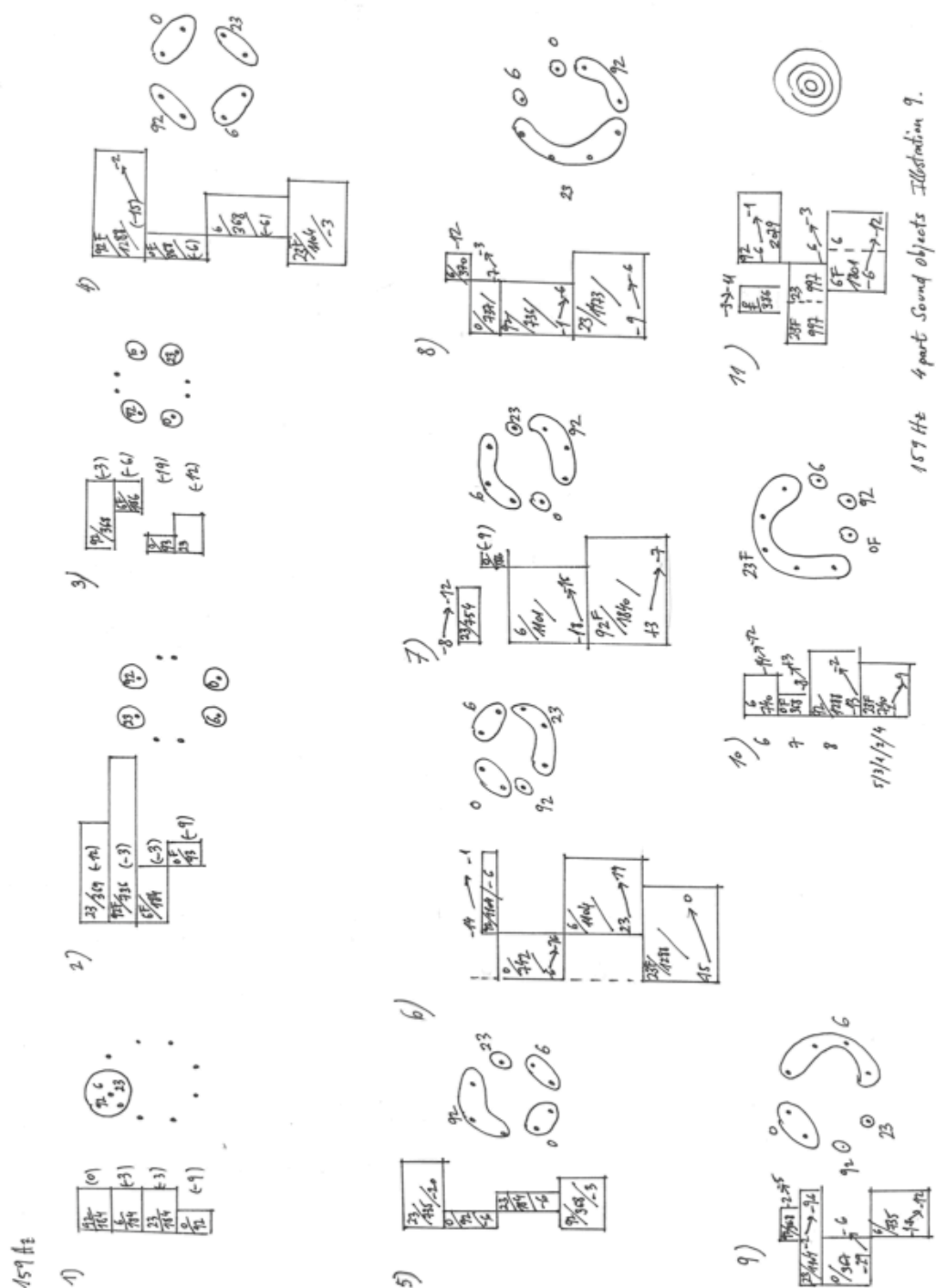
72).¹⁸³

Figure 71. Graph of the spatial and temporal organization of each sound object corresponding to test 5.1.1.

¹⁸³ The graphic representation of spatial and temporal organization for each sound object corresponding to test 5.1.3 are included in the appendix.

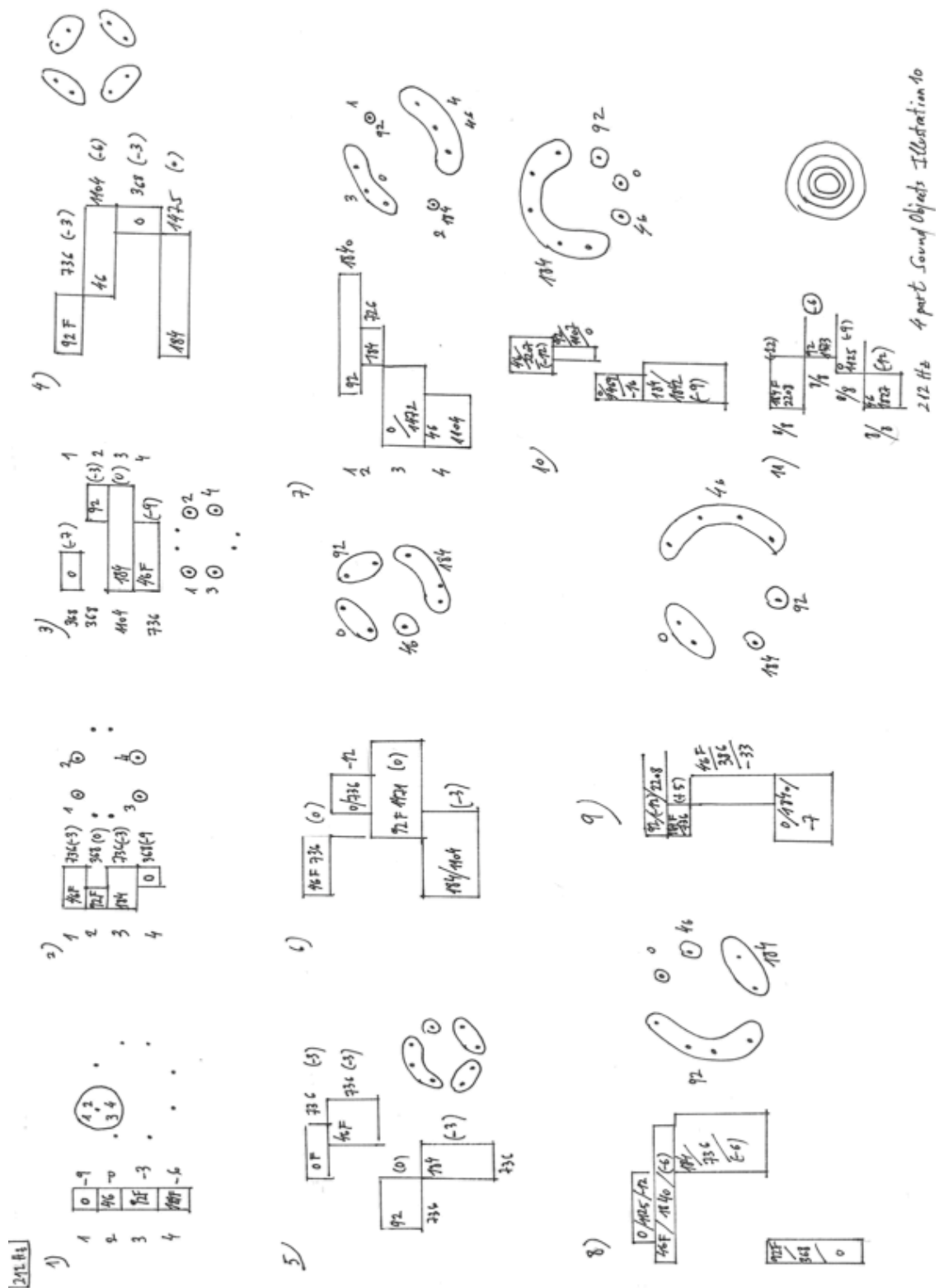


Figure 72. Graph of the spatial and temporal organization for each sound object corresponding to test 5.1.2.

The purpose of test 5.1 is to experiment with the extent to which sound location and sound-space density variations influence the perception of sound attribute and texture variations using various short textures forming sound objects. A sound object is understood, using Michel Chion's definition, as "any phenomenon and sound event perceived as an ensemble, as one coherent unity, and listened to from a reduced listening that aims for the sound itself, independently from its origin and signification."¹⁸⁴

Like the polyphonic textures created in test 4.4, each sound object uses four textures with the same frequency, but each one uses different relative and absolute distances (see tests 4.2 and 4.3). In addition, each texture presents two differentiated sound qualities, depending on the use or omission of fade-in and fade-out envelopes. As shown in the previous figures, the textures using fade-in fade-out envelopes¹⁸⁵ are differentiated from the others by the letter "F" after the frequency.

To perceive to what extent different sound location and sound-space densities influence the perception of sound attribute, rhythm, and texture variations, sound objects are repeated eleven times using different temporal and spatial organizations of the four each texture.

In order to differentiate each texture as much as possible, sound spatialization follows the principle of no overlapping. To preserve this principle, each sound object follows eleven complementary absolute position rows, which present each texture through different sound-space densities and sound locations respecting the principle of no overlapping (figures 73 and 74).

An exception is made with sound object 1, where all four textures are radiated from a single sound source (sound-space density 8/1), and sound object 11, where all textures are spread throughout the same eight loudspeakers (sound-space density 8/8). These situations are accepted because it is necessary to experience and evaluate how sound objects are perceived using the highest and lowest sound-space densities. In addition, they contribute

¹⁸⁴ "(...) tout phénomène et événement sonore perçu comme un ensemble, comme un tout cohérent, et entendu dans une écoute réduite qui le vise pour lui-même, indépendamment de sa provenance ou de sa signification" (Chion, Michel, *Guide des objets sonores – Pierre Schaeffer et la recherche musicale*, 1983, Buchet/Chastel, Paris, p. 34) (translated by the author).

¹⁸⁵ Normally both the fade in-fade out envelopes are 10 ms long, and become automatically shorter as soon as the length of the notes in the 8 or 5-note groups are less than 10 ms.

to more sound attribute, texture, and sound-space density contrasts between the sound objects.

1-	1111-1111	2-	1111-1111	3-	3333-3333	4-	1111-3333
	1111-1111		2222-2222		4444-4444		2222-4444
	1111-1111		7777-7777		5555-5555		5555-7777
	1111-1111		8888-8888		6666-6666		6666-8888
5-	3331-1222	6-	1111-3333	7-	3331-1222	8-	1133-5577
	4444-4444		2222-4444		4444-4444		2222-2222
	5555-7777		5555-5555		5555-5555		4444-4444
	6666-8888		7778-8666		7778-8666		6666-8888
9-	1111-3333	10-	1111-1111	11-	1234-5678		
	2244-6688		2222-2222		1234-5678		
	5555-5555		3333-3333		1234-5678		
	7777-7777		4468-8755		1234-5678		

Figure 73. Absolute position rows for sound objects with frequencies of 159 and 212 Hz.

1-	6666-6666	2-	1111-1111	3-	2222-2222	4-	1111-2222
	6666-6666		3333-3333		4444-4444		3333-5555
	6666-6666		6666-6666		5555-5555		4444-6666
	6666-6666		8888-8888		7777-7777		7777-8888
5-	1111-1111	6-	1111-2222	7-	1111-1111	8-	3311-2244
	2224-4666		3335-5777		2224-4666		5555-5555
	3333-5555		2222-4444		3335-5777		6666-6666
	7777-8888		8888-8888		8888-8888		7777-8888
9-	1111-2222	10-	5531-1244	11-	1234-5678		
	3333-3333		6666-6666		1234-5678		
	4444-4444		7777-7777		1234-5678		
	5577-8866		8888-8888		1234-5678		

Figure 74. Absolute position rows for sound objects with a frequency of 318 Hz.

Test 5.1 shows that sound attribute and texture variations derived from sound location and sound-space density variations are not as well perceived as with sound continuums. The main reasons are that

- 1) the duration of each texture is too short, and there is no time to identify each texture,
- 2) the use of two sound qualities, i.e. with and without fade-in and fade-out envelopes, mask other variations produced by sound location and sound-space density variations,
- 3) the use of textures with the same frequency and note duration but different relative and absolute distances mask the perception of sound attribute and texture variations produced by sound location and sound-space density variations, and
- 4) each texture inside each sound object is presented only one time in one absolute position, and the immediate movement from two contiguous absolute positions and sound-space densities does not occur. As already shown in tests 1.1.5 and 1.2.5, the perception of sound attribute and textures variations is inversely proportional to the temporal distance between two contiguous sound-space densities, as it occurs with the successive sound objects.

Even though the sound objects are perceived as not identical through the eleven successive repetitions, sound location and sound-space density variations contribute very little their differentiation.

However, like continuums, which can be used in different sections of the same piece as in *Polyphonic Continuum*, sound spatialization contributes to the creation of variations of the same sound objects, so they can be repeated without being recognized. The audio files corresponding to test 5.1 present the eleven sound objects two times, one in the original order (see figures 71 and 72, pp. 156-157), and another in the retrograde (i.e. the complete audio file containing the eleven sound objects is played in reverse). This variation reverses both the temporal order of the textures inside a sound object – i.e. the original order of the four textures inside one sound object 1234 is heard 4321 – and the temporal order of the sound objects – i.e. the original order 1, 2, 3, ...11 is now heard 11, 10, 9, 8, etc. The spatial arrangement here is inverted, so each texture changes its position from front to rear or left to right (see figure 7, p. 40). Using such variations it is possible to use the same sound objects to create new sound objects, as the original ones are not recognizable when they are repeated.

4.2.4.1 Further Studies with Sound Objects

Test 5.2 tries to solve some of the problems that appeared in test 5.1, and presents the same textures used in tests 5.1 but with some variations (see figures 75 and 76).

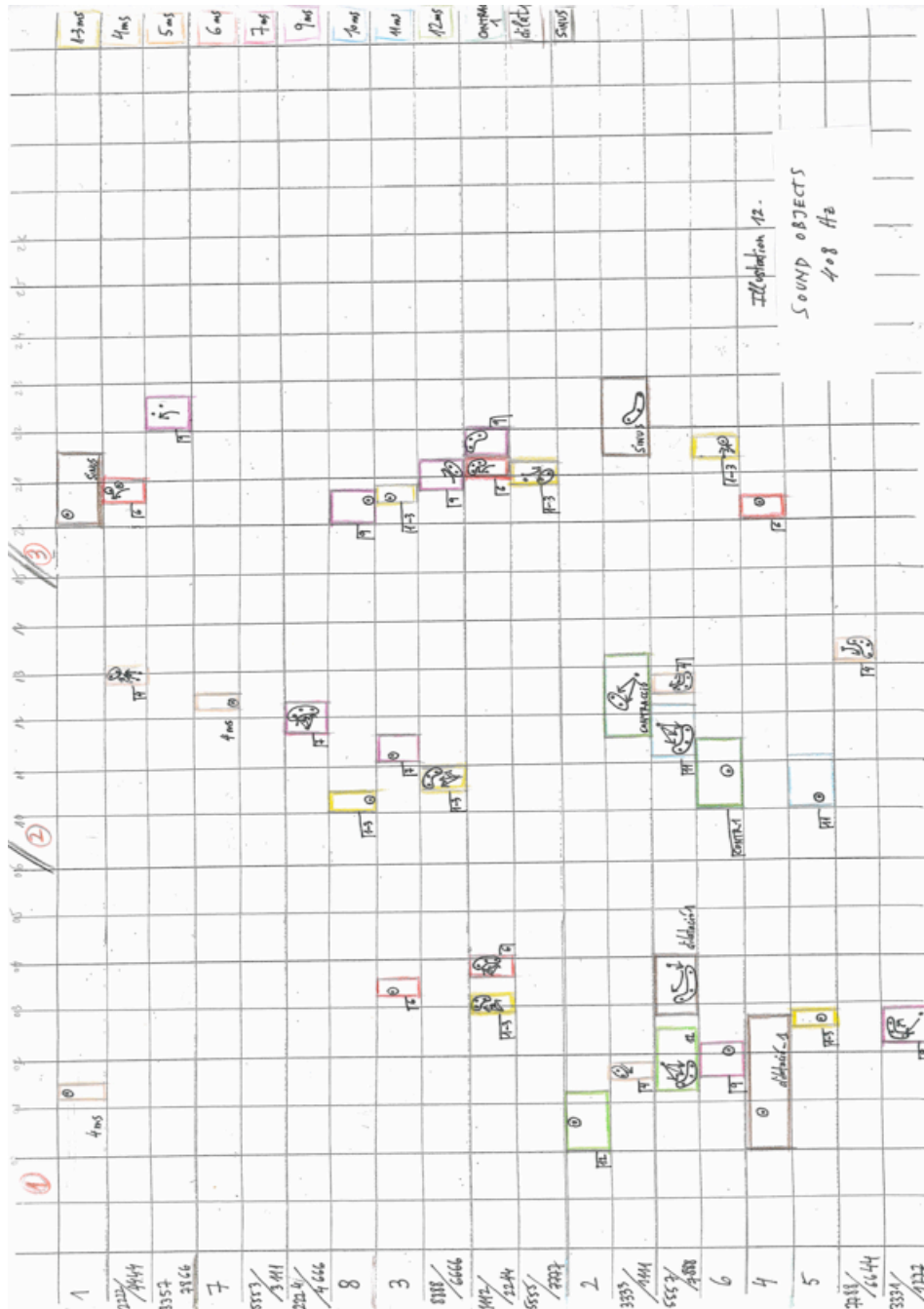


Figure 75. Graph of the spatial and temporal organization of each sound object corresponding to test 5.2.1, 5.2.2, 5.2.3.

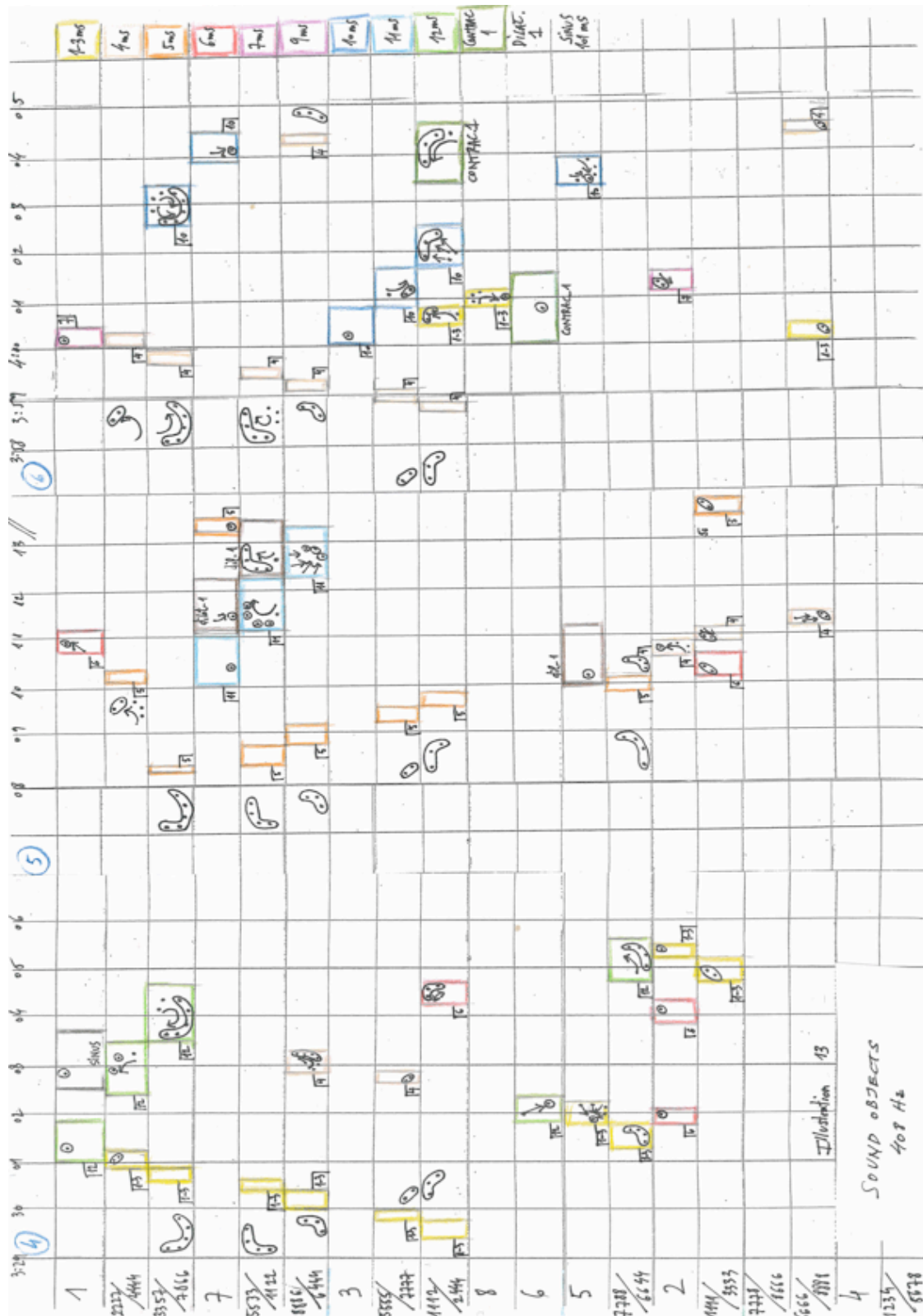


Figure 76. Graph of the spatial and temporal organization of each sound object corresponding to test 5.2.4, 5.2.5, 5.2.6.

First, each texture is longer in relation to test 5.1, so the listener can identify each texture more easily and follow its spatial movement. Second, each texture is presented two or more times, one immediately after the other through different absolute positions, so it is possible to perceive more sound attribute and texture variations between them. Third, the type of sound signal is now expanded to triangle waves and square waves, so they contribute to more dynamic sound objects. Fourth, the number of textures is increased, as each sound object includes 4, 5, or 6 sound textures with the same frequency but different note durations as well as relative and absolute distances, although only four occur simultaneously.

Figures 75 and 76 above show the movement of each texture through the different absolute positions (indicated in the left margin) and sound-space densities as well as the temporal organization of each texture in relation to one another.

Like test 5.1, test 5.2 shows that the sound attribute and texture variations derived from sound location and sound-space density variations are not as well perceived as with the previous tests using sound continuums. The main reason is that they are masked as soon as different types of sound signals, note durations, or relative and absolute distances are used.

However, sound spatialization provides variety and dynamism to the overall perception of the sound objects. Even though the perception of sound attribute, rhythm, and texture variations are significantly masked by other variations, they do occur and contribute to the differentiation of the sound objects.

Indeed, sound movement does provide dynamism and sound clarity to the sound objects, especially when it is possible to recognize one texture and follow its spatial movement through different sound locations. When the trajectories of sounds in space are recognized, it is possible to create a dialog between them, which contributes variation and contrast between similar musical elements, as is the case of the sound objects.

The separation of each component following the principle of no overlapping (see subchapter 3.6) each component to be better perceived and provides sound clarity and transparency to the sound objects, which is very important to perceive the dialog between sound movement and sound perception.

5 Summary

This chapter explains the elaboration of the sound material used in the compositions presented in part 2 of this thesis. The different types of sound materials are elaborated using 8-note groups, which constitute their most elemental formal structure. Depending on how many 8-note groups are played successively, the sound materials are divided in two categories: gestural (attacks, gestures and sound objects), and textural (sustained tones, continuums, and textures).

Each sound material is tested using 8-note groups with different sound signals, frequencies, note durations, relative and absolute distances, and relative and absolute positions; they are evaluated in relation to their ability to produce the perception of sound attribute, rhythm, and texture variations related to sound localization and sound-space density variations. These evaluations are described in more detail at the end of each test included in the appendix.

The most important conclusion is that textural sound materials are most efficient for the perception of cause-effect relations between sound localization and sound movement, and the perception of sound attribute, rhythm, and texture variations. The reason is that in order to perceive such dialog, sound material must undergo no variations in time to frequency, sound quality, or relative and absolute distances. In addition, the listener needs some time to identify each texture and follow its different sound locations and sound-space densities. In the case of gestural sound material, the duration of each texture is too short, and the listener has no time to identify each texture and follow its movement. In addition, using short note durations derived from sound location variations are not as important as with longer note durations.

As sound movement cannot supply enough dynamism, gestural sound materials use other types of sound signals, and notes with or without fade-in and fade-out envelopes, which mask significantly the perception of sound attribute, rhythm and texture variations produced by sound location and sound-space density variations, and the dialog between sound movement and sound perception.

Only when using a static sound material, i.e. with invariable sound signals, frequencies, note durations, and relative and absolute distances, such as sustained tones and continuums, is this dialog fully achieved.

To be sure, the perception of this dialog is the most important feature of the compositions presented in part 2 of this thesis, especially *Polyphonic Continuum* and *Musical Situation 1*, as it permits the creation of a successful musical discourse using sine waves and other time invariant sound signals divided into small units spread in space through different sound locations and sound-space densities.

Chapter 5. DESCRIPTION AND ANALYSIS OF THREE ACOUSMATIC COMPOSITIONS BASED ON AMPLITUDE, SOUND LOCATION, AND SOUND-SPACE DENSITY VARIATIONS

This chapter explains and analyses three acousmatic compositions: *Topos*, *Polyphonic Continuum*, and *Musical Situation 1* included in part 2, which represent the practical part of this research. Analysis covers both the inner and outer form of the pieces, i.e. sound material, form, and the arrangement of the sound sources in space (sound space). It explains as well other important aspects of the compositions where space and sound movement play an important role, such as the perception of diffuse sound fields, the perception of cause-effect relations between sound movement, and the perception of sound attribute, rhythm, and texture variations.

Each composition uses different types of gestural and textural sound materials described in chapter 4. *Topos*, for instance, is based on sound materials that can be classified as gestural, as it uses mainly attacks, gestures, and sound objects. On the contrary, the sound materials used in *Polyphonic Continuum* and *Musical Situation 1* are textural, as they use continuums and sustained tones respectively.

The goal of these compositions is to create a dynamic musical discourse based on the perception of pitch, loudness, tone color as well as rhythm and texture variations derived from the spatial arrangement of sounds through different sound locations and sound-space densities. In this sense, the inner and outer forms of *Polyphonic Continuum* and *Musical Situation 1* are so related to space that it would be impossible to perceive their musical discourses without using sound spatialization.

The first formal structure consists of dividing a tone with a particular frequency in small units called notes, and arranging them in 8-note groups with particular relative and absolute distances. These parameters are related to the temporal organization of the notes in the 8-note groups.

The second structural element is the assignment of a spatial position to each one of the notes in the 8-note groups, so the initial continuous pure tone radiated by one loudspeaker is transformed into successive 8-note groups radiated by eight loudspeakers spread in space. One layer of sound is transformed into eight layers, each one

corresponding to one loudspeaker (see figure 40, p.105). This spatial organization is referred to as relative position (see chapter 3.3.1). As a consequence of this spatial organization, the notes in the 8-note groups are perceived with pitch, loudness, and tone color variations that occur together with sound localization. In addition, changing the amplitude levels of the notes in the 8-note groups creates rhythmic patterns, which are a direct consequence of the division and spatialization of the notes in the 8-note groups, as they are not created a priori.

The next formal organization of the 8-note groups is called absolute position (see chapter 3.3.2), which is deduced from the relative position. The relative position, which organizes the 8-note groups in space using eight loudspeakers, is reorganized using different amounts of loudspeakers, from one loudspeaker to eight loudspeakers. The absolute position varies the sound-space density of the 8-note groups, which go from sound-space density 8/1 (one loudspeaker radiates all the notes in the 8-note groups), or sound-space density 8/8 (the 8-note groups are radiated by eight loudspeakers). From this spatial organization emerges the perception of multiple rhythm and texture variations, in addition to pitch, loudness, and tone color variations that result from molding the 8-note groups using a different number and position of loudspeakers. Again, these rhythms and textures are not created a priori: they are functions of sound spatialization.

In relation to the outer form, sound spatialization is used as well to differentiate between sections using the same exact sound material. *Polyphonic Continuum*, for instance, repeats the first five sections but inverts its sound spatialization (see figure 7, p. 40). Therefore, sections 6 to 10 are differentiated from sections 1 to 5 by using different sound spatializations only, not by using other continuums with other sound signals, frequencies, note durations, amplitude envelopes, etc. Two identical sections are differentiated by particular pitch, loudness, tone color, rhythm, texture, and sound localization variations, which are all functions of sound spatialization.

Consequently, it can be stated that sound spatialization is a *conditio sine qua non* to perceive these pieces.

It is also essential to restate that the main characteristic of the musical discourses of all three pieces, especially *Polyphonic Continuum* and *Musical Situation 1*, is the cause-effect relation between sound movement and the perception of sound attribute, rhythm, and texture variations (see subchapter 3.7). When such cause-effect relations are not perceived,

the musical discourse suffers. The main reason is that in order to perceive pitch, loudness and tone color variations that occur together with sound localization, it is necessary to use sine waves and other time invariant sound signals. As a consequence of using sound signals with a simple timbre, the resulting sound material is perceived as static when these cause-effect variations are not perceived.¹⁸⁶

After a certain time both sound materials and sound signals become monotonous, no matter how dynamic the sound spatialization or the use of multiple gestures, textures, and sound objects may be. In the case of *Topos*, for instance, due to the permanent change of sound parameters such as sound signals, frequency, and amplitude, and the use of multiple sound materials such as attacks, gestures, sound objects, and textures, the cause-effect relations between sound movement and sound perception are not evident or are very difficult to isolate from other variations. In addition, the type of sound signals used cannot generate attractive gestures and sound objects, at least for a long period of time, because they use sound signals that are too static and predictable. This is the main reason why *Topos* has a duration of three minutes, much shorter than the other two compositions. As the perception of cause-effect relations supports long compositions using the same type of sound signals, *Polyphonic Continuum* and *Musical Situation 1* have durations of twenty and twenty-two minutes respectively.

Topos is the less successful than the others, precisely because it uses

- 1) different types of sound material, i.e. attacks, gestures, textures, and sound objects,
- 2) three types of sound signals that vary constantly and rapidly,
- 3) two differentiated sound qualities, i.e. notes with or without fade-in and fade-out envelopes, and
- 4) very short gestures and sound objects, changing permanently and rapidly.

¹⁸⁶ As pointed out by Smalley, the interest of a musical discourse relies on the possibility to perceive variety at different structural levels, which includes sound itself: "It is fair to say that much electroacoustic music does not offer sufficient hierarchical variety. This occurs where the types of sounds and the structural continuity direct one to listen continuously in a global, high-level mode. With textured structures it is very easy for the composer, listening too hard to the textural material, to be deceived into thinking that there is lower-level interest within a texture when there is not. And music which deals mainly in broad, high-level, gestural sweeps with little internal ineters, may not offer much to the listener on repeated hearings. A rewarding balance of perceptual interest at a variety of structural levels is unfortunately more rare than it should be." (Smalley, 1997, p. 113).

As it is demonstrated in chapter 4, when many temporal variations occur at the same time (frequency, amplitude, rhythm, timbre, type of sound signals, and sound materials), they mask or attenuate significantly the perception of sound attribute variations that occur together with sound localization and sound-space density variations.

The only sound temporal parameter that can be used without implying a decrease in the perception of sound attribute and texture variations produced by sound location and sound-space density variations is amplitude, especially when the curve of the amplitude envelope is too mild and gradual to create any attack and decay that could be perceived as a musical gesture. In addition, such long amplitude variations produce long and progressive changes in loudness, which are perceived together with important tone color variations. Amplitude variations are very important in the compositions *Musical Situation I* and *Polyphonic Continuum*.

Another important consequence of using a musical discourse based on the cause-effect relations between the perception of sound attribute, rhythm, and texture variations produced by the movement of sounds in space is the perception of time flow, which is different depending on the use of gestural or textural musical structures. As pointed out by Smalley, gestures imply a forward motion provoked by the energy of an external impulse, which is nonexistent in textures. In textures, the primary strong impulse is inexistent, and the energy is dilated in time, stretching the musical gesture. As a consequence, the attention is focused on internal activity instead of the forward motion.¹⁸⁷

In the case of the compositions presented here, the internal activity involves changes in the position of sounds in space, which is the cause for the perception of sound attribute and texture variations. The attention is focused on what occurs in space and its consequences on the perception of sound, while time is perceived as a function of the changes that occur in space.¹⁸⁸

¹⁸⁷ Smalley, 2007, pp.35-58.

¹⁸⁸ The possibility to organize and move sounds in space rescues music from its motionlessness, which occurs as soon as the relations between successive musical moments are not perceived. This is the case of the music of Anton Webern, and is inherent as well in serial music and any music that is constructed by the sum of independent musical moments. G. Deleuze and C. Pardo talk extensively about this problematic of contemporary music (Deleuze, Gilles. 1998, *Boulez, Proust y el tiempo: ocupar sin contra*, Archipiélago vol. 32, Madrid; Pardo, Carmen, 1998, *Imagen i medida de un espacio sonoro: Ligeti y K. Stockhausen*, Sociedad Española de Musicología vol.XXI, n. 1, Madrid; Pardo, Carmen, 1998, *Discurrir sobre nada: reflexiones en torno a John Cage*, Archipiélago vol. 32, Madrid; and, Pardo, Carmen, 1999, *Laberintos sensibles: el sonido en el espacio*, Universidad Autónoma Metropolitana, Version vol. 9, México,).

This chapter includes a detailed description of each composition in relation to the type of sound material and form, and evaluates the degree of dynamism achieved when the sound material goes through amplitude, sound location, and sound-space density variations.

5.1 *Topos*

Topos explores the importance of the perception of sound attribute and texture variations associated with the movement of sounds in space using a mixture of gestural and textural sound materials, which in this composition implies the use of attacks, gestures, sound objects, and textures. Therefore, the musical discourse presents a constant and rapid variation among different sound signals, frequencies, and sound materials, together with more extended and temporally invariant textures.

In order to emphasize the perception of sound attribute and texture variations produced by sound location and sound-space density variations, both the sound material and its movement in space have to be well-identified and followed by the listener. Sound spatialization and sound movement can be used to better identify each layer by supplying a spatial distance between them. The movement of each layer through identifiable sound trajectories also permits the differentiation of similar simultaneous layers.

Therefore, in *Topos* the functions of sound movement and sound spatialization are oriented:

- 1) to achieve musical clarity and transparency by physically separating the musical events,
- 2) to achieve musical relief by moving sounds in space following recognizable sound trajectories, and
- 3) to supply each sound material with a spatial shape and sound directionality.

All these functions are intended to emphasize the perception of sound attribute and texture variations related to sound location and sound-space density variations. Thanks to sound spatialization and the principle of no overlapping, sound materials are more easily

identified and followed by the listener.

5.1.1 Sound Material

Topos uses four types of sound material described in chapter 4:

- 1) 5-note group attacks and short gestures (see subchapter 4.2.3 and test 3.1)¹⁸⁹,
- 2) sound objects (see subchapter 4.2.4 and test 5.1), and
- 3) textures (see subchapter 4.2.2 and test 4.3).

Each sound material uses different types of sound signals, namely sine waves, square waves, and triangle waves, with frequencies of 53, 159, 212, 318, 477, 795, and 954 Hz. At the same time, each sound material uses particular note durations, relative and absolute distances, relative and absolute positions, and sound-space densities. In addition, both textures and sound objects use 8-note groups with or without fade-in and fade-out envelopes, which imply the perception of two very differentiated sound qualities.

5.1.2 Form

The 5-note group attacks are the most important structural elements, as they serve to organize the musical material that appears throughout the piece, namely gestures, sound objects, and textures.

The attacks are organized throughout the piece following five steps. First, five types of 5-note groups are created using five different note durations: 1, 6, 11, 23, 46 ms. Each one of these 5-note groups is repeated eight times following the (O) relative position row (see figure 40, p. 105), so the total number of attacks is forty, i.e. eight attacks for each one of the five note durations. The frequencies of each note in the 5-note groups follow the frequency row showed in figure 57 (p. 125), and the distances between the notes follow the relative distance row showed in figure 58 (p. 126) (see figure 77).

¹⁸⁹ All tests can be found in appendix II.

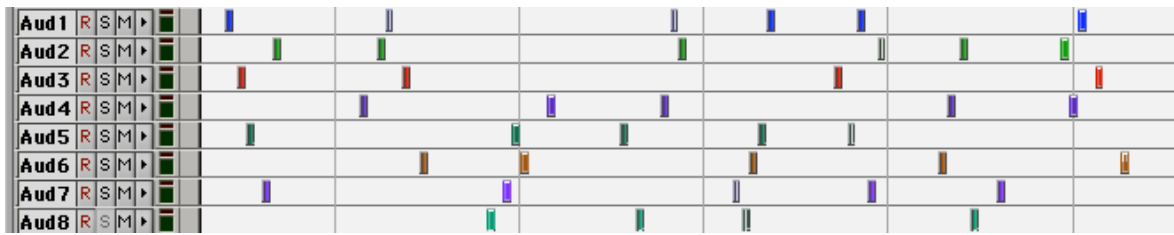


Figure 77. Pro Tools image showing eight attacks corresponding to the Original (O) relative position rows.

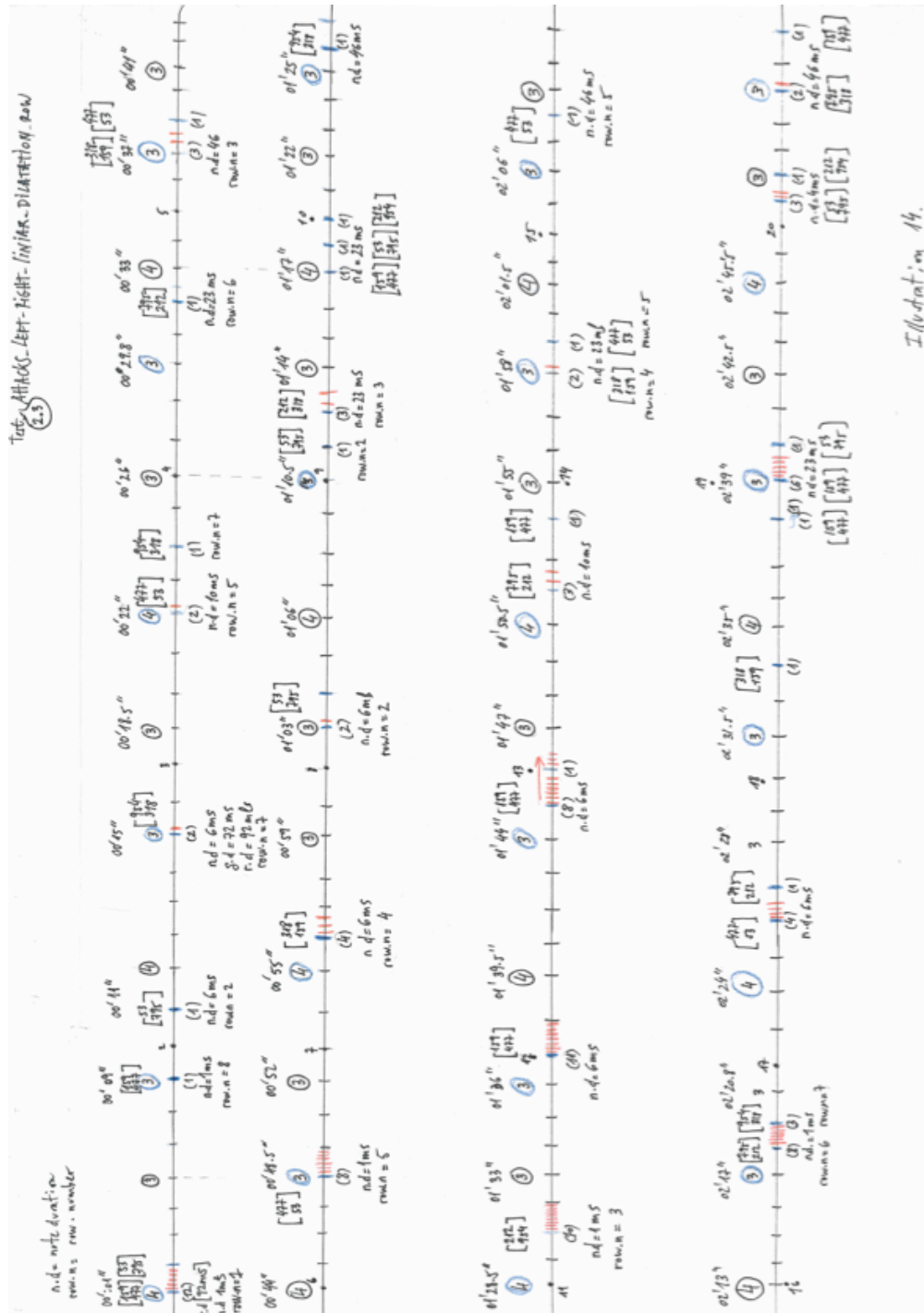
Second, these five groups of eight attacks are organized sequentially beginning with the shortest note duration (1 ms) and ending with the longest note duration (46 ms). So the chronological order is: eight attacks with a note duration of 1 ms, followed by eight attacks with a note duration of 6 ms, 11 ms, 23 ms and finally 46 ms.

Third, these forty attacks are organized in time following a fixed (absolute) distance between them determined by the tempo quarter note 53,33,¹⁹⁰ so each successive attack occupies the temporal position of each successive quarter note.

Fourth, this sequence of forty attacks is repeated four times, although only a few attacks are played each time the sequence is repeated. However, at the end of the four repetitions all forty attacks are played.

Fifth, the selection of the attacks for each sequence is derived by dividing the forty attacks following subgroups of 4+3+3 attacks. These subgroups are used to select the attacks that are played, so during the first ten attacks only one or two attacks of the first four and last three are played, and in the second ten attacks only the attacks within the middle three are played. This pattern is repeated throughout the sequence of forty attacks and the four series of forty attacks (see figure 78).

¹⁹⁰ This tempo is borrowed from a previous acoustic composition of mine, *Eppur si muove* (2008), which represents my first attempt to use different temporal positions of the same note groups (similar to the ones used for the sound objects described in this thesis) to create the perception of sound attribute variations. The tempo of each individual section was deduced from the previous one, creating a tempo modulation (similar to Carter's string quartets) between sections. The composition *Topos* followed this piece, and at the beginning I borrowed some of its formal organization. However, only the tempo and the temporal organization of each attack remained. This tempo optimally separates each attack, and the speed of successive attacks was dynamic enough.


 Figure 78. Temporal organization of the attacks used in *Topsos*.

The selected attacks of each sequence are as follows:

1) sequence 1, attacks 1, 2, 8, 10, 15, 21, 23, 30, 35, 36 (10)

2) sequence 2, attacks 5, 12, 18, 19, 26, 27, 31, 32, 33, 39 (10)

- 3) sequence 3, attacks 3, 9, 16, 17, 22, 24, 28, 29, 37 (9)
- 4) sequence 4, attacks 6, 7, 13, 14, 20, 24, 25, 26, 34, (35), 38, 40 (11)

The selected forty-one attacks and their organization in time represent the main structure of the piece, as they serve to organize the rest of sound material that constitutes the composition, as shown in figure 79.

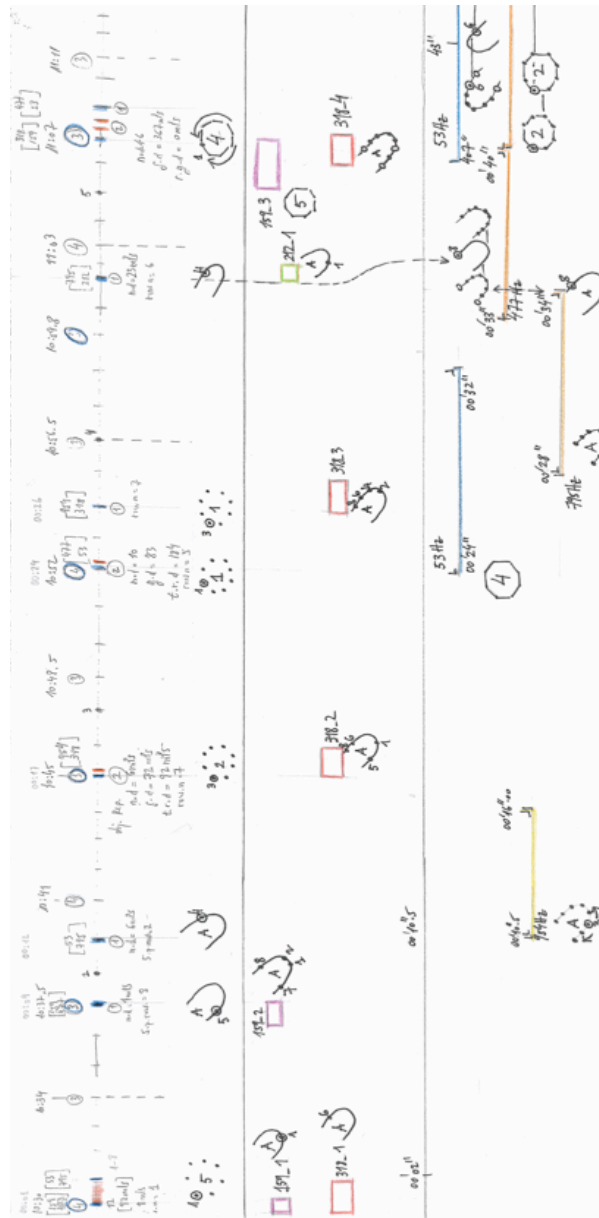


Figure 79. Page 1 of the graphic score of *Topos*.¹⁹¹

¹⁹¹ For the complete score see figures 94, 95, and 96 (pp. 222, 223, and 224).

On one hand, the frequencies of the first and last notes of the attacks are anticipated and/or prolonged by sound objects and/or by textures with the same frequency. When the textures and sound objects are long enough, they create polyphonic situations with other attacks, sound objects, and textures. Which attacks are anticipated and prolonged by sound objects and textures is decided in an intuitive way, with the purpose of creating a dynamic musical discourse.

5.1.3 Sound Space

Sound space is organized to facilitate the spatial functions mentioned above, namely:

- 1) to differentiate the sound materials one another,
- 2) to allow the creation of sound trajectories and to mold sounds with a spatial shape and directionality,
- 3) to create dialogs between sound materials and sound locations, and
- 4) to potentiate the perception of sound attribute and texture variations produced by sound location and sound-space density variations.

For this purpose, the sound space is divided in four aural hemispheres: (A) front-left, (B) front-right, (C) rear-left, and (D) rear-right, and in five “circles” around the audience. Each area and circle consists of 8 sound sources (see Figure 15, p. 66).

On one hand, single 8-note groups attacks are radiated by one sound source only (sound-space density 8/1), while gestures are spread along one of the circles using the left-right sound-space dilation rows (see figure 80).

On the other hand, sound objects and textures can be radiated by one sound source only (sound-space density 8/1), occupy one area (sound-space density 8/8), or can be spread into a circle surrounding the audience (sound-space density 8/8) (see figure 17, p. 68).

As shown in figure 80, sound materials are spread in areas and circles respecting the principle of no overlapping (see subchapter 3.6), so simultaneous attacks, gestures, sound objects, and textures are radiated through areas and circles without using the same

loudspeakers. As both areas and circles share the same sound sources, to achieve the principle of no overlapping it is necessary that the sound sources used to radiate a sound material through one circle are not used for the sound material played in the areas.



Figure 80. Graph of the principle of no overlapping between areas and circles.

Figure 80 shows three different possibilities. When no circles are used, layer 1 can be radiated through the eight sound sources of an area (see example 1). In the case where two sound materials (layers 1 and 2) are radiated simultaneously by one area and one circle, i.e. when one sound material (layer 2) is spatialized using a circle while the other (layer 1) occupies one area, it is necessary that the sound material that is spatialized in one area is radiated through six sound sources instead of eight, so the other two can be used by the circle (see example 2). If three sound materials are played simultaneously using two circles and one area (layers 1, 2, and 3), only four sound sources per area would be used, as the other four would be used for the sound material radiated using two circles (see example 3).

Topos can be played using either eight or forty real sound sources, or WFS,¹⁹² which permits the virtual positioning and movement of forty-two sound sources. At the present time, only the version using eight sound sources and WFS have been experienced. However, the sound space achieved using forty real sound sources is supposed to be the best of the options for several reasons:

¹⁹² In the case of WFS, the forty sound sources would be virtual instead of real. This means that the actual position of the sound source is not achieved by a real loudspeaker, but through the sum of multiple sound sources. This system is based on Huygen's wave theory, which states that any wavefront can be regarded as a superposition of elementary spherical waves, so that a wavefront can be synthesized by a number of secondary point sources. Following the Kirchoff's quantified version of this theory, Berkout created a spatialization system using linear arrays of loudspeakers that produce the same wavefront in the listening area as would be produced by a real source in any position behind or in front of the array (Berkhout, 1998).

- 1) using eight sound sources, the number of loudspeakers for each area is reduced from eight to two, and the number of circles is reduced from five to one. This reduction implies that the principle of no overlapping cannot be achieved, as simultaneous sound materials played in areas and circles are forced to share the same sound sources, and
- 2) using eight sound sources, sound-space density variations are drastically reduced. In relation to the areas, the maximal sound-space density is reduced from $8/8$ to $8/2$. In relation to the circles, sound-space density is the same although the number of circles is reduced from five to one (see figure 81).

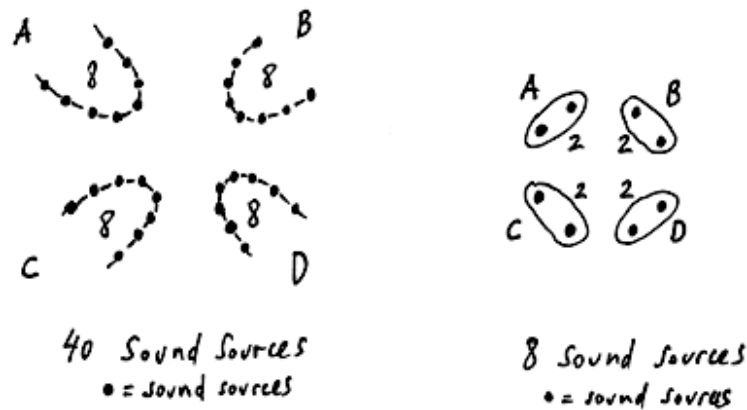


Figure 81. Graph showing the reduction of sound sources in the areas from eight (max. sound-space density $8/8$) to two (max. sound-space density $8/2$).

3) using two sound sources per area impedes the perception of the same sound attribute, rhythm, and texture variations that are perceived when using all possible sound-space densities, i.e. from $8/1$ to $8/8$.

4) WFS presents problems in the reconstruction of amplitudes and positions, so they are not as precise as when using one real sound source (loudspeaker) for each sound.¹⁹³

¹⁹³ In theory, WFS would require infinite secondary sound signals (loudspeaker arrays) situated both in the vertical and horizontal planes to exactly reproduce a sound signal. In reality, the WFS system at the TU Berlin has only a finite number of loudspeakers (2700) restricted to the horizontal plane. This simplification

5) using forty real sound sources increase also sound transparency and sound clarity, as each sound material is separated from the others a certain distance, so it is more differentiated and its sound qualities can be better perceived.

6) using forty real sound sources implies that a certain spatial depth inside each sound material is also perceived, as they are positioned at different distances in relation to the listener (see figure 15, p. 66)

7) using forty sound sources implies as well that the sound space is more dynamic, as more sound trajectories, sound locations as well as sound attribute, rhythm and texture variations are perceived.

5.1.4 Summary

Topos attempts to prove that a good perception of sound attribute and texture variations associated to sound location and sound-space density variations is inversely proportional to the amount of variations in relation to sound signals, frequencies and sound materials. The more active is sound itself in time, i.e. which occurs when it experiments frequency, amplitude and timbre variations in time, less perceptible are the variations produced by sound location and sound-space density variations. The use of gestural sound materials with different frequencies, amplitude envelopes and timbres mask to a great extent the perception of sound attribute and texture variations produced by sound location and sound-space density variations.

Consequently, the dialog between sound movement and the perception of sound attribute and texture variations is in *Topos* almost imperceptible, as it is highly masked by the diversity of sound materials, sound signals and frequencies, and the rapid and permanent changes from one another.

However, the perception of sound attribute and texture variations produced by sound

produces boundaries to the extension of the listening area and can also produce echoes due to diffraction effects at the edges of the array. Using a limited number of loudspeakers together with the distance between them implies an upper limit on the frequencies that can be accurately reproduced (Frank, M., Zotter, F. and Sontacchi, A., 2008, *Localization Experiments Using Different 2D Ambisonics Decoders*, 25th Tonmeisterstagung – VDT International Convention). These statements are supported by the extensive analyses of Ambisonics and WFS undertaken by Enda Bates in his doctoral dissertation *The Composition and Performance of Spatial Music* (2009), where the author points out their virtues and deficiencies in relation to sound localization.

movement does occur, and they contribute to the perception of variety in the sound material, especially textures. This is especially important when the typology of the sound signals (sine waves, square waves, etc.) is characterized by their simple and non-dynamic timbre. To capture the interest of the listener, the spectral structure of sounds must exhibit constant variations in frequency, amplitude, and timbre over time.¹⁹⁴ In the case of *Topos*, the movement of sound in space balances the absence of complex timbres, the use of time-invariant sound signals, and the limited frequency range. In this sense, spatial dynamism counteracts the temporal motionlessness of sounds.

The attacks and gestures are the only sound materials clearly influenced by space. On one hand, the early reflections determine to a great extent the number of notes in the 5-note groups that are perceived and their spatial localization, as a consequence of summing localization and the law of the first wavefront (see subchapter 2.8). On the other hand, the shape and directionality of the attacks achieved by using the right-left sound-space dilation rows is very evident, and help to invigorate the attacks.

The same can be said of the textures, which present almost no variations except for their movement in space. Sound-space density variations give each texture a particular shape and directionality, conferring more dynamism both to textures in particular and to the musical discourse in general.

Therefore, *Topos* shows that using gestural sound materials together with constant and rapid frequency, amplitude, rhythm, and timbre variations to a great extent masks the perception of sound attribute, rhythm, and texture variations produced by sound location and sound-space density variations, although they exist and contribute to a dynamic musical discourse. This proves that only when the sound material exhibits few variations in time, do these types of variations become relevant for the listener.

Consequently, the following compositions use one type of sound material only, avoiding the gestural sound materials and the use of constant frequency, rhythm, and timbre variations.

¹⁹⁴ Howard, 224, p. 119-136.

5.2 *Polyphonic Continuum*

This composition uses continuums only, avoiding the gestural sound materials as well as constant variations of frequency and timbre. The purpose is to emphasize the perception of sound attribute, rhythm, and texture variations associated with sound localization and sound-space density variations.

Continuums represent the second most static sound material after sustained tones, as they maintain the same sound signal and frequency while using variable or invariable relative and absolute distances. Therefore, the type of sound signals and the sound material undergo few or no variations in time, which permit the listener to focus on the movement of sound in space.¹⁹⁵ What the piece offers is, on one hand, the perception of sound trajectories, spatial shapes, and sound directionality achieved as a consequence of the movement of sound through different sound locations and sound-space densities, and on the other, the perception of important sound attribute and texture variations associated with them.

Therefore, *Polyphonic Continuum* creates a dialog between the cause-effect relations between sound movement and the perception of sound attribute and texture variations. Indeed, while sound moves in space, the listener perceives pitch, loudness, tone color, rhythm, and texture variations of the sound material. All these variations are functions of the movement of sound in space, and in fact do not exist without it.

The piece *Polyphonic Continuum* creates a musical situation where the listener must search through the whole sound for what he wants to listen or whatever he finds interesting while immersing the listening in space, like plunging inside a “pool” full of sound.

In contrast to *Topos*, the perception of cause-effect relations between sound movement and sound perception support long durations. Indeed, *Polyphonic Continuum* has a duration of 20 minutes.

This piece can be presented together with the video *Visions of Macbeth* (2009) by the artist Markus Selg (*1972). Even though the images were added once the piece was

¹⁹⁵ The sound signals used in the continuums are sine waves, which are defined as time invariant sound signals, and at the same time most of the continuums use invariable relative and absolute distances. Few temporal variations occur when the continuums use variable relative and/or absolute distances, which is the case of the continuums of 53 and 212 Hz used in the composition.

composed, they are perfectly complemented. The relation between video and music is that both try to overcome the temporal and spatial limitations inherent in painting in one hand, and music on the other. On one hand, the video presented by Selg represents three “paintings” in constant motion, as the figures and objects vary slightly their position, texture, and color. This movement contradicts the consideration of painting as a spatial art fixed in time.

While music is of course considered a temporal art, the perception of time flow is here to some extent avoided by using:

- 1) time invariant sound signals,
- 2) extremely static sound materials with no frequency, timbre, or rhythmic variations over time, and
- 3) a musical discourse focused on the internal activity of the textures created by the continuums, which consists of sound location, sound attribute, rhythm, and texture variations that emerge as a consequence of the movement of sounds in space.¹⁹⁶

5.2.1 Sound Material

Polyphonic Continuum uses five continuums only, each one consisting of a sine wave with a specific frequency and note duration:

1) Sine wave	53 Hz	10 ms
2) Sine wave	212 Hz	23 ms
3) Sine wave	318 Hz	46 ms
4) Sine wave	477 Hz	21 ms
5) Sine wave	795 Hz	08 ms

¹⁹⁶ Stockhasuen describes a similar approach to the perception of time flow in his article *Momentform*, although here musical motionlessness is achieved with a completely different aesthetic. Certainly, in *Momentform* each musical moment is different from the others, as each one uses different parameters concerning pitch, tempi, durations, timbres, etc. As a consequence, the narrative discourse disappears. On the contrary, *Polyphonic Continuum* is based on a type of sound material whose frequency, timbre, and rhythm undergo no variations other than very progressive variations in the amplitude envelopes. Therefore, the attention focuses on what occurs inside the texture, namely the trajectories of sounds in space and the effects of such movement on the perception of pitch, loudness, tone color, rhythm, and textures variations.

Each continuum uses different relative and absolute distances, which can be

- 1) variable, i.e. the distance between the notes in the 8-note groups and the note groups themselves is different, or
- 2) invariable, i.e. the relative and absolute distances are the same and are determined by one unique value.

In *Polyphonic Continuum*, the relative and absolute distance used for each continuum are the following:

- 1) 53 Hz, relative distance: VARIABLE ($0 \geq 52$ ms)
 absolute distance: VARIABLE (± 23 ms)

- 2) 212 Hz, relative distance: INVARIABLE (23 ms)
 absolute distance: VARIABLE ($0 \geq 34$ ms)

- 3) 318, 477 and 795 Hz, relative distance: INVARIABLE (16 ms, 27 ms, 02 ms resp.)
 absolute distance: INVARIABLE (16 ms, 27 ms, 02 ms resp.)

As already mentioned in subchapter 4.2.2.1, the use of variable relative and absolute distances, as is the case of the continuum with a frequency of 53 Hz, is as optimal for the perception of sound attribute, rhythm, and texture variations as the use of invariable relative and absolute distances, as soon as they don't create rhythmic patterns. In the case of the continuums used in *Polyphonic Continuum*, the successive 8-note groups create no rhythmic patterns, and both variable and invariable relative and absolute distances create continuous and homogeneous textures. For more detailed information about the structural organization of the continuums, see subchapter 4.2.2.1.

5.2.2 Form

Polyphonic Continuum consists of five polyphonic situations (I, II, III, IV, and V), separated by long pauses. Each polyphonic situation uses a different combination and number of continuums, with a minimum of three and a maximum of five, as shown in Figure 82. The numbers correspond to the frequency of each continuum, and the dashed lines indicate the continuums that are not played. Only the last polyphonic situation (V) presents all continuums.

(I)	(II)	(III)	(IV)	(V)
53	53	-----	53	53
212	-----	212	212	212
-----	318	-----	-----	318
477	477	477	-----	477
795	-----	795	795	795

Figure 82. List of continuums involved in each polyphonic situation of *Polyphonic Continuum*. Each value corresponds to a frequency in Hz.

These five polyphonic situations are repeated again in the same chronological order using a different spatialization for each continuum. As shown in figure 83, each continuum presents two spatializations, which are indicated below each continuum. Following the sound space defined in figure 16 (p.67), the continuums change from one area to another area, as for instance from area C to area D of the continuum with a frequency of 53 Hz in section I (00'14'' to 01'46''), or by changing their spatial extension from one area to one circle, as for instance the continuum of 318 Hz in section II (area C to circle 2).

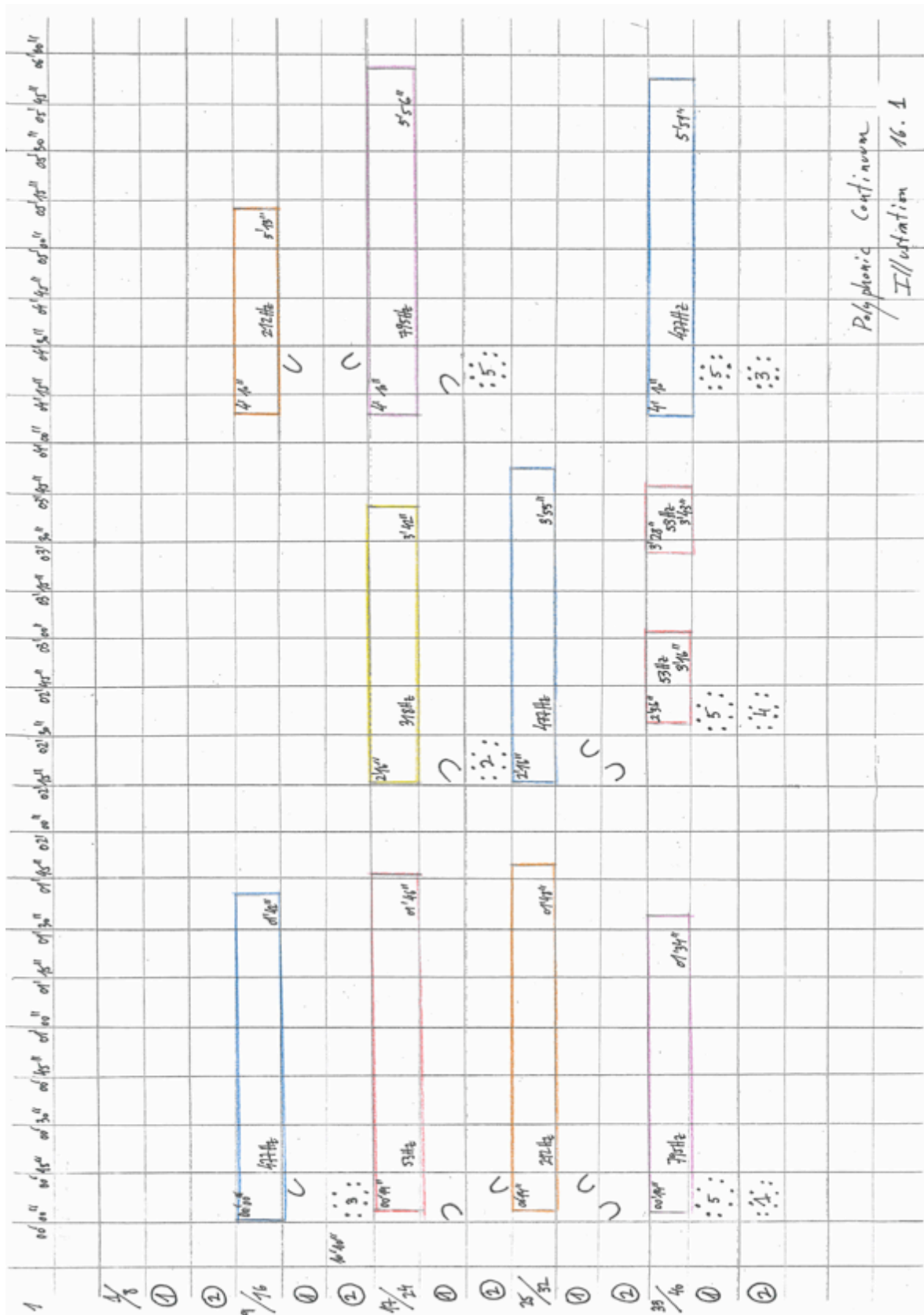


Figure 83. Graphic score of Polyphonic Continuum, polyphonic situations I, II and III.

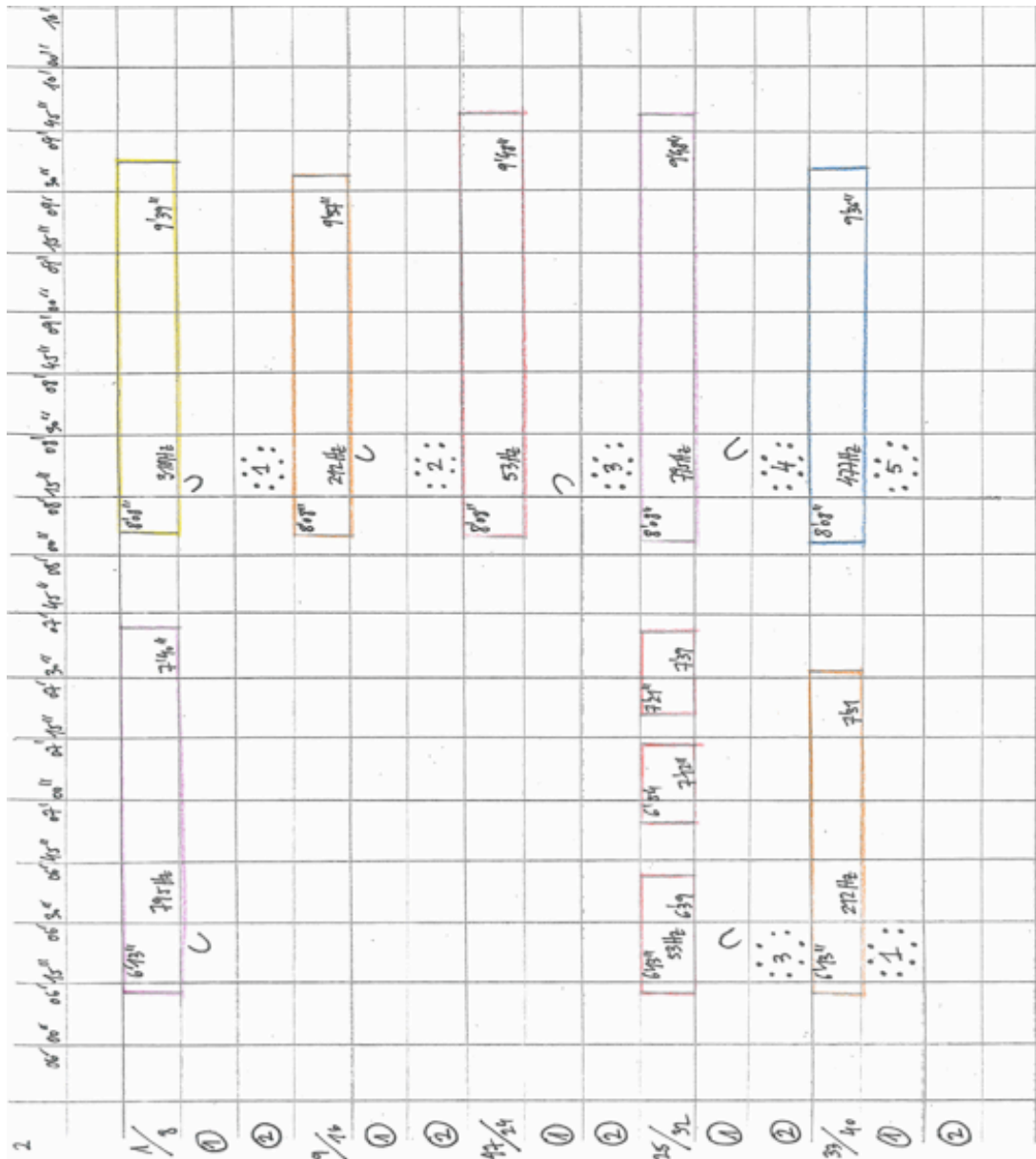


Figure 83 (cont.). Graphic score of Polyphonic Continuum, polyphonic situations IV and V.

Using eight sound sources implies that each area is reduced from eight sound sources to two, so sound-space density variations are to 8/1 and 8/2, and only one circle around the audience is used instead of five circles (see figure 81, p. 177).

As the perception of sound attribute, rhythm, and texture variations depends on the number of sound sources, the version of *Polyphonic Continuum* using eight sound sources employs the same spatialization as the polyphonic situations VI, VII, VII, IX, and X shown

in figure 84, because they use more circles than areas. This spatialization is repeated again although spatially inverted (see figure 7, p. 40).

The form of each continuum, besides its frequency, note duration, and relative and absolute distances, is defined by the position and movement of the 8-note groups through different relative and absolute positions and sound-space densities. The spatial movement of sound following these parameters provides each continuum a dynamic and variable shape, sound-space density, and sound directionality. At the same time, the movement of sound in space implies the perception of sound attribute, rhythm, and texture variations for each continuum, which otherwise would not be perceived. In both cases, i.e. using forty or eight sound sources, sound spatialization is the only formal parameter used to create variations on the same musical situations.

In addition to the movement of the notes inside the 8-note groups through different sound locations and sound-space densities, this composition incorporates another movement: the movement of the listener. As a consequence of this movement, it is possible to open the musical discourse to multiple perspectives (see subchapter 1.4). With the possibility to move freely around the room, each listener can perceive his or her own version of *Polyphonic Continuum*.

Consequently, in addition to being presented to the public in concert, where everybody is seated, the piece can be presented as an installation, where every listener can enter and leave the performance at will, as well as to move freely in the room. At the centre of the room the listener perceives one version of *Polyphonic Continuum*, as from this position, the amplitude levels and envelopes of each continuum create a particular musical discourse. By moving around the room, the listener modifies the distances between him and the sound sources, thus modifying again the levels and amplitude envelopes, perceiving and thus creating other versions of the piece.

5.2.3 Sound Space

Polyphonic Continuum can be performed using eight loudspeakers arranged as in figure 19 (p. 69) or using forty loudspeakers arranged as in figure 16 (p. 67). Using WFS implies that the forty sound sources are virtual instead of real, although they follow the same spatial arrangement as using forty loudspeakers.

With forty loudspeakers or WFS, the sound space is organized, like *Topos*, in four areas (A, B, C, D) and five circles (1, 2, 3, 4 and 5). The main purpose of dividing the sound space in four aural hemispheres is:

- 1) to achieve musical clarity by differentiating spatially each continuum, and
- 2) to create spatial dialogs between continuums located in different areas.

The use of simultaneous continuums creates a polyphonic situation where the perception of sound attribute, rhythm, and texture variations on one continuum occur simultaneously with other variations on the other continuums. In this sense, besides using different frequencies for each continuum, their spatial separation permits better differentiation.

When the continuums are spread using circles instead of areas, they are also well-differentiated thanks to the use of different frequencies, as well as the perception of recognizable sound trajectories. In addition, dividing sound into small units (notes in the 8-note groups) and spreading them in space contributes to sound transparency, as each continuum is full of empty space through which other sounds can be heard. Sound clarity and transparency are better perceived when using forty sound sources, as it is possible to spatialize each continuum using the principle of no overlapping.

To emphasize the perception of sound attribute, rhythm, and texture variations of each continuum in a polyphonic situation, the sound sources (loudspeakers) of the areas are arranged in space differently compared to *Topos*. In this case the shape of the sound space permits the listener to enter inside one area and perceive in much greater detail the sound attribute and texture variations produced by sound location and sound-space density variations of one particular continuum.

This also enables musical perspective, as inside the areas the listener automatically increases the spatial distance in relation to the other continuums, which are heard more or less in the background depending on the distance and amplitude in relation to the other areas and continuums. This experience is more or less perceptible depending on the dimensions of the room. The bigger the distances between the loudspeakers and areas, the greater the sound clarity, sound transparency and sound perspective.

5.2.4 Summary

Both sound signals and sound material used in *Polyphonic Continuum* are very static. However, sound and musical dynamism is achieved by using sound location and sound-space density variations, together with amplitude variations. Sound and musical dynamism refer here to the perception of pitch, loudness, tone color, rhythm, and texture variations, all of which are functions of the movement of sounds in space through different sound localization and sound-space density variations.

Consequently, the number and position of the sound sources is crucial, as the amount of dynamism depends on the possibility to use as many sound locations and sound-space density variations as possible.

Another important parameter that contributes to sound and musical dynamism is amplitude. The curves of the amplitude envelopes used in *Polyphonic Continuum* are extremely smooth and gradual. Therefore, they are not used to create gestures or sound shapes, but to achieve a certain depth and sound perspective. In addition, amplitude envelopes have important consequences for the perception of loudness and tone color variations.

One of the most important characteristics of this piece is that sound attribute, rhythm, and texture variations are consequences of spatial parameters, i.e. sound localization and sound movement, through relative and absolute positions and sound-space density variations. In fact, the musical discourse is based on the dialog between sound attribute, rhythm, and texture variations, and the movement of sounds in space.

In addition, the form of the piece is defined to a large extent through the positions of the continuums in space. On one hand, the same continuums are repeated in several polyphonic situations using sound spatialization as the only parameter that differentiates each repetition. On the other hand, sound spatialization permits repeating the first five polyphonic situations using different areas and circles for each continuum. In both cases, sound spatialization prevents the listener from identifying or recognizing that the exact same continuums are being repeated.

Sound movement and sound spatialization become a fundamental formal element of sound, sound material, and the musical discourse. Without the use of sound spatialization and sound movement, the perception of pitch, loudness, tone color, rhythm, and texture

variations would not occur.

5.3 *Musical Situation 1*

This composition is based on sustained tones, which represent the most static type of sound material explained in chapter 4. Indeed, most of the sustained tones used in *Musical Situation 1* involve one type of sound signal, one frequency, one note duration, and an invariable relative and absolute distance of 0 ms.

However, the most important difference in relation to continuums is that the notes in the 8-note groups go through relative position variations only, while the absolute position remains always 1234-5678. Therefore, sound-space density is permanently 8/8, as sustained tones use no other absolute position and sound-space density variations. The exclusive use of relative position variations impedes the perception of rhythm and texture variations produced by sound-space density variations, and the 8-note groups are perceived with sound attribute variations only, which are derived from the movement of the notes in the 8-note groups through different relative positions.

As already mentioned in test 1.5, relative position variations alone are not dynamic enough to create a satisfying musical situation. This composition, however, shows that it is possible to create a musical discourse based on the perception of sound attribute variations produced by the movement of the notes in the 8-note groups through different relative positions, when they are accompanied by:

- 1) amplitude variations, which imply important variations in loudness and tone color, and
- 2) the use of notes with or without fade-in and fade-out envelopes, which create two very different sound qualities of the same notes in the 8-note groups.

In *Musical Situation 1* amplitude variations create important rhythm, loudness, and tone color variations of the same sustained tone. The tone color variations are so important that it is possible to use the same sustained tone several times, and create a completely different musical situation, as each time new tone colors, textures, and spatial depths, i.e. diffuse sound fields, are achieved.

The notes in the 8-note groups using no fade-in or fade-out envelopes are perceived with a transient sound at the beginning and end of each note, which create a granular texture together with the pitched notes. Like *Polyphonic Continuum*, the spatial distances between the notes in the 8-note groups is here also very important for sound transparency, as it affords a spatial perspective or relief between these two superimposed sound qualities.

In addition, *Musical Situation 1* uses the progressive dilation of the notes in the 8-note groups. This note dilation is used in two ways. First, the sustained tones are introduced by a progressive dilation of 1 ms in the duration of the notes in the 8-note groups until they reach the note duration assigned to each frequency. In this case, the relative and absolute distances are always 0 ms, so the velocity of succession of the notes in the 8-note groups decreases while the note duration increases (see figure 84). This note occurs, for instance, at the very beginning of the piece, and is later repeated several times. In all cases, the sound quality goes from non-pitched to pitched, which is reinforced by using simultaneous sustained tones and notes with or without fade-in and fade-out envelopes.

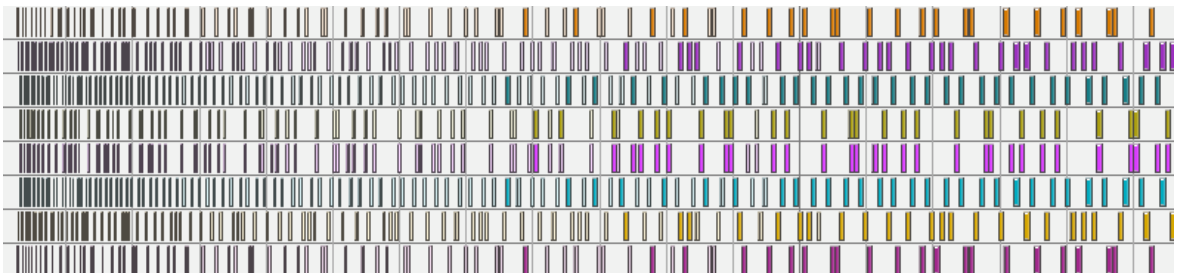


Figure 84. Sound dilation of the notes in the 8-note groups with relative and absolute distances of 0 ms.

The second type of sound dilation consists of a progressive dilation of 1 ms of the notes in the 8-note groups, although in contrast to the previous case, they keep a fixed relative and absolute distance, which in this case are the same. Therefore, the notes in the 8-note groups gradually dilate by 1 ms, from 1 ms until they reach the fixed relative and absolute distance. In other words, the relative and absolute distances gradually diminish by 1 ms until they become 0 ms (see figure 85). This is the case, for instance, of the sustained 448 Hz tone (12'10'' to 13'30''), that dilates by 1 ms from 1 to 226 ms.

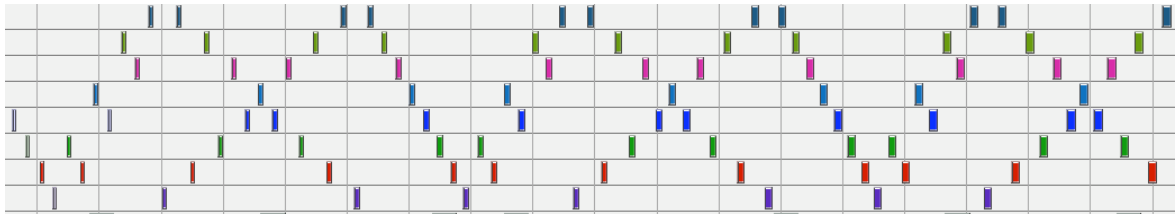


Figure 85. Sound dilation of the notes in the 8-note groups using the same relative and absolute distances as the final note duration.

This type of sound dilation is also important because the notes in the 8-note groups are perceived with a gradual transition from non-pitched to pitched. In addition, sound localization becomes increasingly blurred together with the appearance of the pitched sounds, in comparison to non-pitched sounds. This blurriness in relation to sound localization that appears together with longer note durations can be interpreted as a dramatic component of sound dilation, as the notes dissolve into space, losing their capacity to be spatially differentiated.

5.3.1 Sound Material

Musical Situation 1 is based on eleven sustained tones, whose sound signals, frequencies, and note durations are as follows:

- | | |
|---|--|
| 1. Frequency: 53 Hz
Sound signal: Sine Wave
Note duration: 368 ms | 2. Frequency: 159 Hz
Sound signal: Sine Wave
Note duration: 180 ms |
| 3. Frequency: 212 Hz
Sound signal: Sine Wave
Note duration: 92 ms | 4. Frequency: 318 Hz
Sound signal: Sine Wave
Note duration: 46 ms |

- | | |
|--|--|
| <p>5. Frequency: 408 Hz
Sound signal: Sine Wave
Note duration: 1 ms sound dilation
from 1 ms to 226 ms</p> | <p>6. Frequency: 272 Hz
Sound signal: Square Wave
Note duration: 56 ms</p> |
| <p>7. Frequency: 426 Hz
Sound signal: Sine Wave
Note duration: 1 ms sound dilation
from 1 ms to 208 ms</p> | <p>8. Frequency: 448 Hz
Sound signal: Sine Wave
Note duration: 1 ms sound dilation
from 1 ms to 266 ms</p> |
| <p>9. Frequency: 284 Hz
Sound signal: Sine Wave
Note duration: 52 ms</p> | <p>10. Frequency: 1224 Hz
Sound signal: Square Wave
Note duration: 55 ms</p> |
| <p>11. Frequency: 212 Hz
Sound signal: Triangle Wave
Note duration: 92 ms</p> | |

It presents as well some interludes that use a gestural sound material like short textures and attacks. All textures used in this composition come from test 4.3, i.e. textures whose 8-note groups undergo no relative or absolute distance variations. The frequencies used for the textures are 53, 159, 212, 318, 477, 795, and 954 Hz. However, it is not possible to specify the note durations or the relative and absolute distances of each particular texture, as they were manipulated several times to find the optimal superposition, duration, and spatialization, and at some point in the process they lost their identification names and references.

5.3.2 A Step Beyond Micro-Polyphony?

The acoustic effect of *Musical Situation 1* could be compared to the piece *Atmospheres* (1961) by Ligeti (1923-2006), in the way it creates a sound mass by accumulating multiple melodic lines which are not possible to differentiate from the whole. In the case of *Musical Situation 1*, however, the “melodic” movement of the sustained tones is not achieved by varying the frequency of the notes in the 8-note groups. Instead, it is achieved by dividing each sustained tone into small fragments, and placing them in

different locations in space so each fragment reaches the auditory system from different directions. In doing so, each note is perceived with microtonal pitch variations, creating a microtonal melody, together with loudness and tone color variations. Without the movement of sound in space, each sustained tone would be perceived as an invariable continuous tone, and the polyphonic texture would be perceived as a simple harmonic structure, with no inner “melodic” movement of the voices.

5.3.3 Form

The piece consists of nine expositions and five interludes as shown in figure 86.

	EXP.1	INT.1	EXP.2	EXP.3	INT.2	EXP.4
Layer 1	212	212	212	212	212	212
Layer 2	318	318	318	318	318	318
Layer 3	159	159	159	159	159	159
Layer 4	53	53	53	53	53	53
Layer 5	-----	-----	-----	408	TEXT.	272/1224
	EXP.5	INT.3	EXP.6	INT.4	EXP.7	INT.5
Layer 1	212	212	212	212	212	212
Layer 2	318	318	318	318	318	318
Layer 3	159	159	159	159	159	159
Layer 4	53	53	53	53	53	53
Layer 5	426/272	TEXT.	448	-----	284	TEXT.
			EXP.8	EXP.9 (Ending)		
	Layer 1		212	212		
	Layer 2		-----	318		
	Layer 3		159	159		
	Layer 4		53	53		
	Layer 5		272/212	272/212		

Figure 86. Formal structure of *Musical Situation 1*: EXP. = Exposition, INT. = Interlude, and TEXT. = Textures.

Each polyphonic situation contains four to six different sustained tones (layers), each one with a different frequency in Hz. A dashed line instead of a frequency signifies an empty layer. Besides sustained tones, the interludes also present textures, which are indicated as TEXT. Each exposition has a duration of ca. two minutes, and the interludes a

duration of ca. ten seconds. Both interludes and are separated by silences with a duration of ca. six seconds. Only one long silence (twenty seconds) followed by a long interlude (fifty-four seconds) appears at the second half of the piece (13'45" to 15'20") (see figure 87).

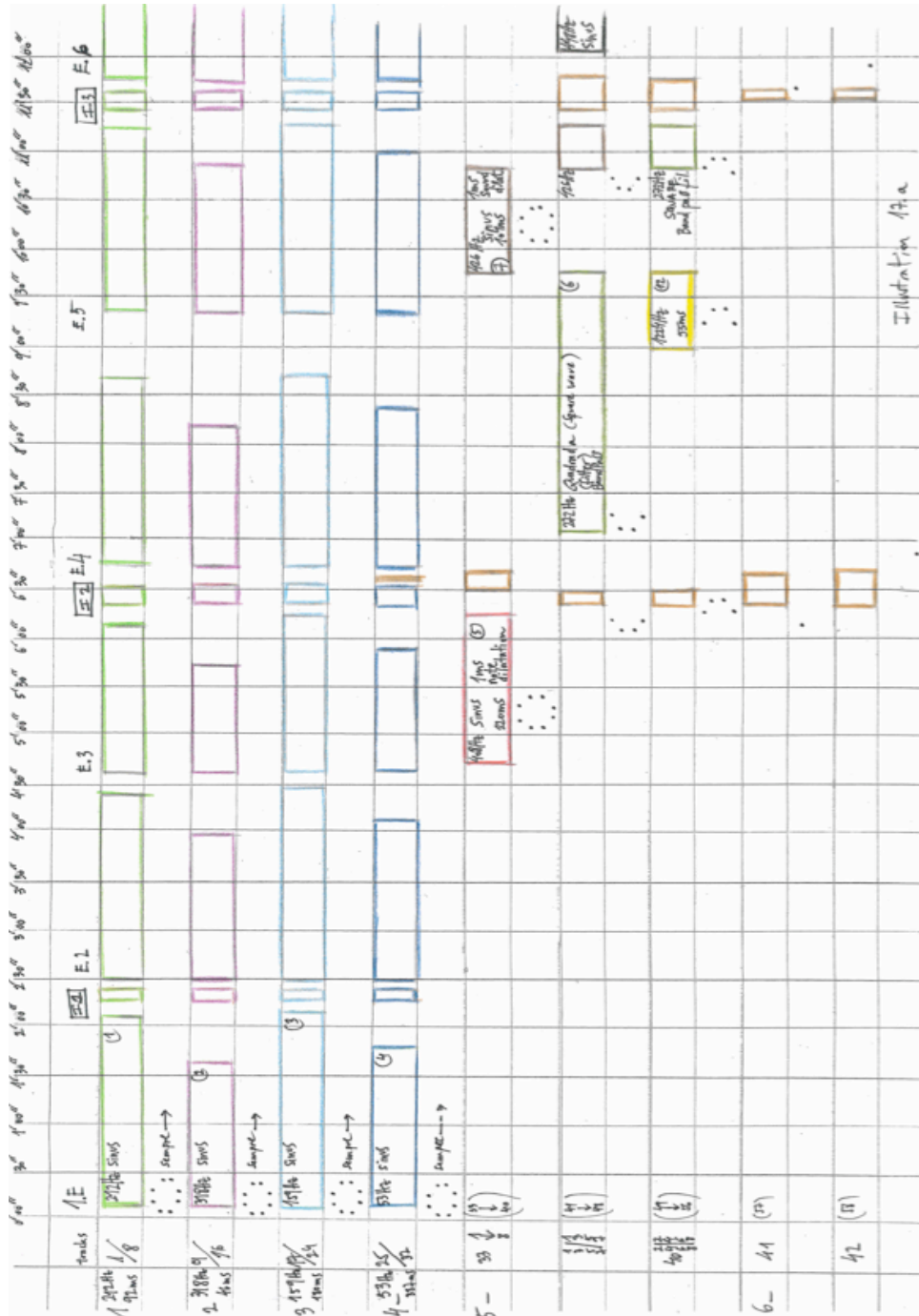


Figure 87. Graphic score of *Musical Situation 1*.

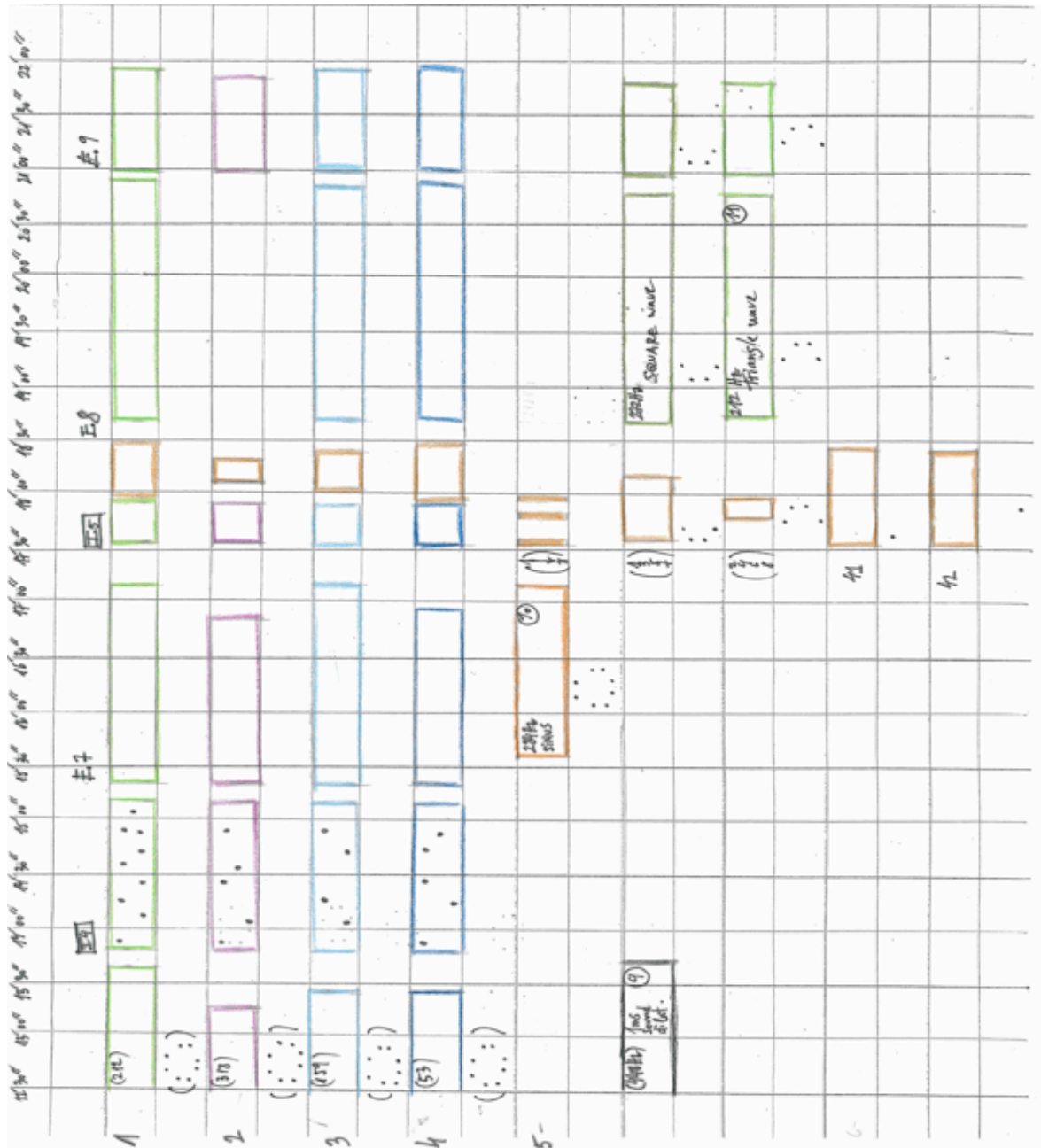


Figure 87 (cont.). Graphic score of *Musical Situation 1*.

As it can be observed, all polyphonic situations, with the exception of exposition 8, contain the same four sustained tones (53, 159, 212, and 318 Hz), which constitute the basic harmonic structure. These frequencies correspond to an octave and a perfect fifth (53, 159 Hz) and its transposition an octave above (212 and 318 Hz). Therefore, the resulting harmonic color is neutral and open, which makes it possible to differentiate each frequency and to perceive the sound attribute variations produced by relative position variations. The

division of the tone into small units called notes, the movement of these notes in space, and the perception of sound attribute variations between them prevent the perception of a static and definite harmony, as the perception of an octave and a fifth is not as evident as when the notes are presented continuously by one sound source. On the contrary, what is perceived is a transparent and ethereal mass of sound, which is the consequence of filling a tone with space, and the harmonic color is thus barely recognizable, or at least unimportant.

Expositions 1, 2, 4, 5, 6, and 8 are introduced by a progressive sound dilation from 1 ms to the specific note duration assigned to each sustained tone, keeping both relative and absolute positions at 0 ms (see figure 84, p. 190), which produces a very dynamic and dramatic beginning, as the sound quality goes from non-pitched to pitched. With sound dilation, notes gain the battle with time, as pitched sounds can finally be fully manifested and perceived. Using sound-space density 8/8 emphasizes this important dramatic moment, as sound surrounds the audience from all directions and fills the space with sound.

From Exposition 3 until the end, different frequencies are added to the basic harmonic structure. What is most important is that they contribute to create dynamism

- 1) by introducing new harmonic colors,
- 2) by differentiating each polyphonic situation harmonically, and
- 3) by introducing new rhythmic dialogs with the notes in the 8-note groups between the old and new sustained tones.

5.3.4 The Process of Creating *Musical Situation 1*: Toward a Dynamic Musical Situation.

5.3.4.1 Static versus Dynamic

Exposition 1 and Interlude 1 represent the most static musical situations in the piece because the sound and spatial parameters, i.e. timbre, pitch, amplitude, harmony, note duration, rhythm, relative and absolute distances, and relative and absolute positions, do not change. The only parameter that constantly changes is the relative position, and, as a

consequence of the movement of sound in space, the notes in the 8-note groups are perceived with pitch, loudness, and tone color variations.

Although such variations are indeed perceived, after a while exposition 1 becomes quite static. Clearly, relative position variations alone cannot create a dynamic musical situation. Exposition 1 introduces another timbre by using the transient sounds that occur when the fade-in and fade-out envelopes of the notes in the 8-note groups are removed. The contrasting sound materials between pitch and transient sounds create a new dynamic situation, which is emphasized by:

- 1) the recognition of sound trajectories that appear with the transient sound, and
- 2) the perception of a spatial relief between the pitched and non pitched sounds.

These resources are used in other expositions with different results, as they are more or less evident depending on the amplitude relations among the notes in the 8-note groups in one sustained tone, or among different sustained tones, creating at the same time spatial dialogs between them.

Another important dynamic element is introduced at the end of each exposition, as each sustained tone finishes at different moments. The gradual absence of sustained tones produces new harmonic colors, as well as new timbres and rhythmic patterns.

All these resources are used in exposition 1 and interlude 1. However, if we want to use the same sound material for the oncoming sound blocks and maintain interest and dynamism it is necessary to introduce additional variations.

5.3.4.2 The Importance of Amplitude Variations

Amplitude variations represent, together with relative position and the use of notes with fade-in and fade out envelopes, the third main formal element of this piece. Indeed, independent amplitude changes of the notes in the 8-note groups provide infinite rhythmic variations no the same sustained tone. At the same time, amplitude variations are perceived together with important loudness and tone color variations (see subchapter 1.5).

Exposition 2, for instance, uses the same material as exposition 1 and interlude 1 but

lowers the amplitude level by ca.30 dB. This circumstance creates a completely new musical situation that is accompanied by the perception of a diffuse sound field (see subchapter 2.7). In addition, subtle differences in the amplitude envelopes of some of the eight layers involved in each sustained tone create the perception of constantly renewed rhythmic patterns, which at the same time are perceived as spatial dialogs between the notes in the 8-note groups. All these variations together create a dynamic musical discourse, and no other variations, such as the use of transient sounds, are needed.

Each polyphonic situation, from exposition 3 until the end, present new harmonic colors by adding new frequencies together to the basic harmonic structure. These new frequencies provide considerable dynamism to the piece, as they help to differentiate the polyphonic situations from one another. However, each polyphonic situation remains the same for at least two minutes. During these two minutes, besides the new sound quality produced by the already mentioned transient sounds, the only parameters that supply dynamism are sound movement and amplitude changes.

5.3.5 Sound Space

The sustained tones are arranged in five concentric regular octagons or circles as shown in figure 15 (p. 66). Each octagon is slightly displaced from the previous one by a certain angle and radius, which is the same for the six octagons. The purposes for this spatial disposition are

- 1) to fill space with sound by spreading sounds around the listener in equidistant sound sources, thus achieving a homogeneous sound field,
- 2) to situate each sustained tone at a different distance from the centre, thus differentiating them better, and
- 3) to accentuate the perception of spatial depth and spatial perspective among the sustained tones.

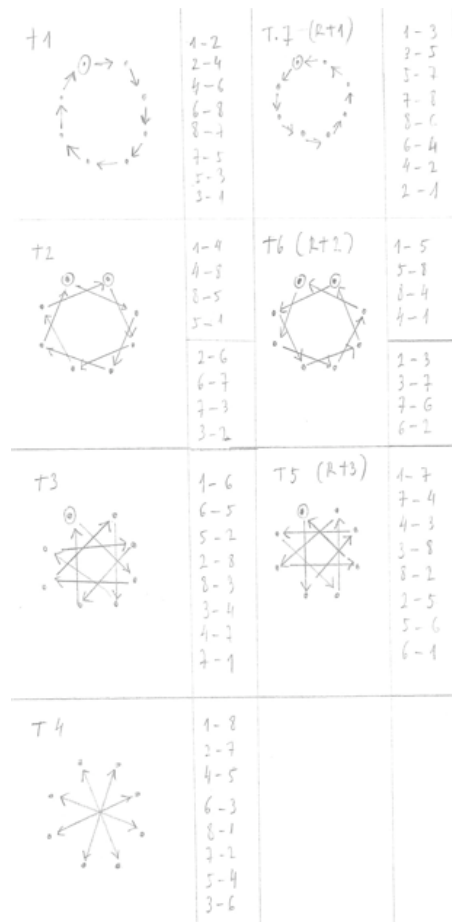
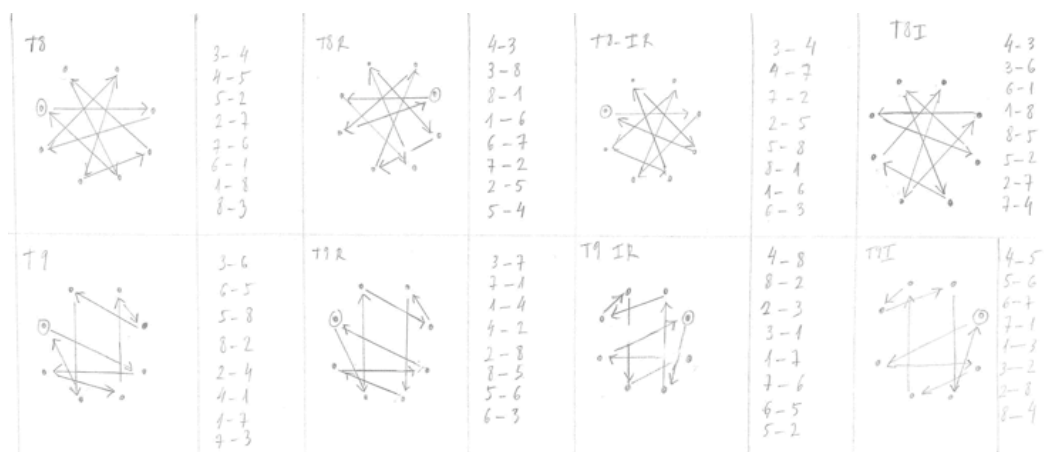
5.3.6 Sound Movement

WFS affords “continuous” sound movements from any point in space to any other. This type of sound movement is used in *Musical Situation 1* only, in addition to the discontinuous movement that occurs already when spreading the notes in the 8-note groups in space. The main reasons why this type of movement is here used are

- 1) to avoid the perception of the same rhythmic patterns, which occurs when the listeners are too close to the sound sources,
- 2) to create rhythmic variations by moving some notes in the 8-note groups closer to other notes situated at distant locations, and
- 3) to create gradual loudness and tone color variations by moving the sustained tones through different circles.

In relation to the first point, during the performances of *Musical Situation 1* it was noticed that the audience situated closer to the loudspeakers perceived some sound sources more than the others, which prevented them from perceiving the desired homogeneous textures. In addition, they were susceptible to perceiving some notes more than others, which could create monotonous rhythmic patterns. Seating the audience more or less at the center of the room a certain distance from the loudspeakers, as in large concert halls, would avoid this problem. However, even though the H-104 room is sufficiently big, the problem still persists.

To avoid this problem, WFS permits moving the notes in the 8-note groups continuously from one source to another, so the rhythmic patterns of one loudspeaker change constantly. Sometimes, only one, two, or four voices move, creating rhythmic interferences with stationary voices. The intention is to create new rhythmic situations and avoid monotonous repetitions. Figure 88 shows different types of sound trajectories of the 8-note groups while figure 89 represents the first page of the graphic score of *Musical Situation 1* showing the sound trajectories for each layer or sustained tone.


 Figure 88. Sound trajectories T1, T2, T3, T4, T5, T6, T7 used in *Musical Situation 1*.

 Figure 88 (cont.). Sound trajectories T8, T8R, T8IR, T8I and T9, T9R, T9IR, T9I used in *Musical Situation 1*.

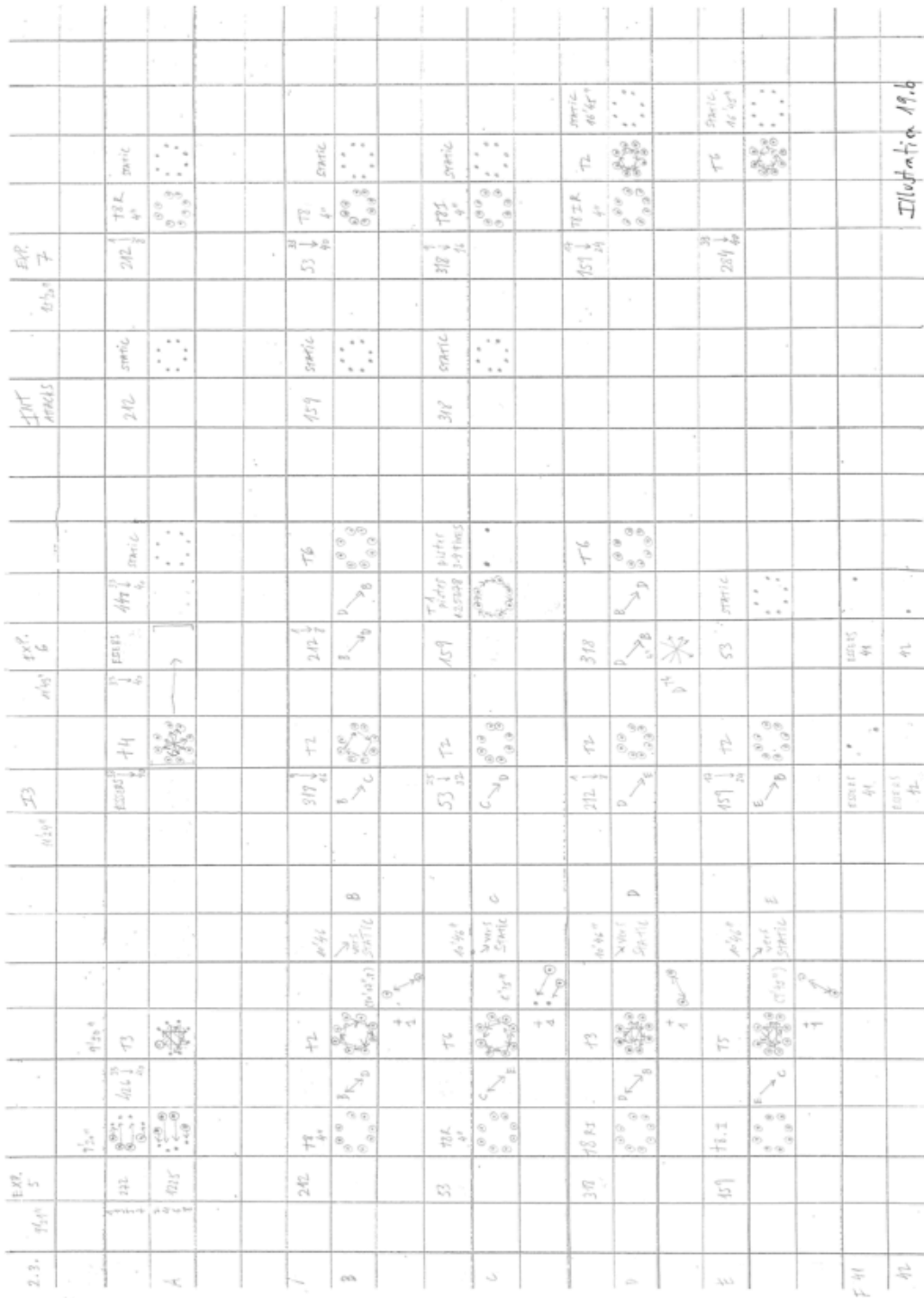


Figure 89. Graphic score of *Musical Situation 1* showing the movement of the notes in the 8-note groups for each sustained tone (page 1 of 3).¹⁹⁷

¹⁹⁷ For the complete graphic score see figures 97, and 98 (pp. 225-226);

The arrows show the direction of the movement. Sound trajectories T7, T6, and T5 are the same as T1, T2, and T3, but the sound moves in the opposite direction, i.e. the original sound direction from point a toward point b, is reversed from point b to point a. This movement is referred to here as retrograde, and is indicated with the letter (R). For instance, T1 represents a cyclic movement to the right, so the notes in the 8-note groups move toward the sound source at the right; following the position and number of the sound sources shown in figure 19 (p.69), sound source 1 moves to sound source 2, sound source 2 to 4, 4 to 6, etc. T7 represents the same cyclic movement as T1, although the sound sources move to the left. Besides retrograde movement, T8 and T9 present two other variables: the inversion (I) and the inversion of the retrograde (RI). The inverted (I) sound trajectory is deduced from the spatial inversion shown in figure 7 (p. 40), where each sound source is assigned to another sound source that represents its inversion. In this case, the numbers that appear next to the sound trajectory indicate the movement of each sound source as shown in the figure.

These sound trajectories are used for the composition *Musical Situation 1*. Figure 89 above shows which trajectories are applied to each sustained tone. *Musical Situation 1* uses six concentric circles identified with the letters A, B, C, D, E, and F, where A is closest to the center (see figure 16, p. 67).

As it can be seen, sound trajectories can be applied inside one circle or between circles. For instance, at exposition 3, circle A radiates a sustained tone with a frequency of 53 Hz using sound the trajectory T6. In this case sound movement remains inside one circle, so sound source 3 moves to sound source 2, both from the same circle. In interlude 1, circle C radiates a sustained 318 Hz tone using sound trajectory T1. However, in this case sound movement goes from circle C to circle A, so moving toward the centre.

Sometimes only some of the notes in the 8-note groups move, as is the case of exposition 3 circle C (212 Hz). In this example, only two sound sources (7 and 1) follow the trajectory T9.

The purpose of organizing the sustained tones in specific circles is to emphasize some frequencies in relation to the others, as mentioned in point 3 above. The reason for this necessity is that all three compositions were created using eight sound sources only, so the amplitude levels were adjusted according to a single distance. As soon as the octagons

are organized in six different concentric distances, the distance and amplitude level of each sustained tone may influence the overall sound. As a obtaining good amplitude balance between the layers is very delicate and subtle task, the distance of each layer in relation to the listener (or the centre of the room) must be adjusted so important aspects of one layer are not masked by the others. Sometimes inside one exposition, the musical protagonist shifts from one sustained tone to another. In these cases, the continuous movement between circles brings the audience closer to the important layer, and moves away the others.

The movement of the sustained tones among circles should also be perceived as a change in the overall tone color, like the effects of amplitude changes. However, after hearing this piece using WFS, it can be said that changes in the harmonic color are not very important, mainly because the movement between circles is too slow and gradual to perceive a clear difference between two tone colors.

In general, the continuous movement of the notes in space is not perceived. This is due to the fact that each continuous tone is divided into small units (notes in the 8-note groups), and each sound source radiates only some of them. Even though sound sources move continuously in space, the fragmented sound material impedes the perception of a continuous sound. Instead, the listener perceives independent sound units, i.e. notes separated from one another by a certain amount of time. The possibility to perceive a sound trajectory depends on how close in time they are; they are especially close when the sustained tone uses note dilation.

5.3.7 Summary

Musical Situation 1 attempts to show that it is possible to create a dynamic musical discourse using almost exclusively relative position and amplitude variations. Besides these variations, each sustained tone presents, as well, three differentiated sound qualities or timbres:

- 1) pitched sounds, which occur when the notes in the 8-note groups use fade-in envelopes,

- 2) non-pitched or transient sounds, which occur either when the notes in the 8-note groups are very short in duration or use long notes without fade-in and fade-out envelopes, and
- 3) the gradual transition between non-pitched and pitched sound through the gradual dilation of the note duration, from 1 ms to the final duration assigned to each sustained tone.

Except for these variations, the other parameters related to time (i.e. frequency, note duration, and relative and absolute distances) and space (i.e. absolute position and sound-space density) remain invariable.

Therefore, the parameters that confer dynamism to the piece are the spatial movement of the notes in the 8-note groups through different relative positions, amplitude variations, the use of pitched and non-pitched sounds, and sound dilation. This is so for four reasons:

- 1) Each sustained tone is perceived with sound attribute variations, i.e. pitch, tone color, and loudness, which occur when varying the position of each note inside the 8-note groups in space.
- 2) Each sustained tone is perceived with important tone color variations depending on the amplitude level, which can vary from *f* to *ppp*.
- 3) Rhythm is not created or designed a priori, but it appears as a consequence of the division of sustained tones into small units, spreading them in space, and using different amplitude levels for each layer (sustained tone). When the amplitude levels of the layers are different, some are more audible than the others, creating rhythms. These rhythms can occur inside one sustained tone or between two or more sustained tones, creating spatial dialogs as well as providing each sustained tone a sound directionality.
- 4) the use of multiple sound sources and sound spatialization, together with specific amplitude levels creates the perception of diffuse sound fields (see subchapter 2.7), which happen when the level of the primary sounds is lower compared to the levels of the reflections and reverberation.

Indeed, all variations that occur in *Musical Situation 1* are functions of space. Certainly, without the spatial movement of the notes in the 8-note groups, the polyphonic situations would be inexistent, and the simultaneous sustained tones would be perceived as a static harmonic sound with little or no internal movement. For all these reasons, as in *Polyphonic Continuum*, space is the foundation of the musical discourse.

At the same time, relative position variations create homogeneous textures in which it is difficult to follow or even perceive the movement of the notes in the 8-note groups in space. In these cases, amplitude level variations create dynamism, as they are perceived together with pitch, tone color, and loudness variations, and at the same time they produce rhythmic patterns that articulate spatial dialogs and achieve a certain sound directionality. Additionally, together with sound spatialization, they create the perception of diffuse sound fields.

6. CONCLUSIONS

This thesis presents an outline of the functions of real space in musical composition, and introduces a new function based on the psychophysics of spatial hearing in order to manipulate the perception of sound attributes such as pitch, loudness, and tone color. This new function differs from the previous functions of space, where sound spatialization is used as a formal element in music, and uses spatialization as a formal element of sound itself, emphasizing the perception of such sound attribute variations to the point that they can be incorporated as a fundamental element of a musical discourse, explored in the three compositions presented here.

Two important techniques or methods involving the formal organization of sound are employed: sound division and sound-space density. First, the sound signals are divided into small units, or notes, organized in 8-note groups, which are radiated by eight loudspeakers arranged in the approximate shape of a regular octagon around the listener. When sound reaches the ears from different directions, the transfer functions occurring at the external ear differentiate them with subtle pressure level, phase, and time variations, which are perceived as pitch, loudness, and tone color variations. In addition to these sound attribute variations, when successive 8-note groups are organized in space following different sound-space densities, they are perceived as well with rhythm and texture variations.

The experiments included in the appendix show that it is necessary to use sine waves or other time invariant sound signals such as square waves or triangle waves, as the perception of pitch, loudness, and tone color variations produced by sound localization are so subtle that they tend to become masked when using sounds with complex spectra or whose frequency, timbre, and amplitude change over time. The same occurs when using melodies, harmonies, motives, sound objects, or gestures that imply constant rhythm and frequency variations.

In order to experience the perception of sound attribute, rhythm, and texture variations as functions of sound location and sound-space density variations, it is necessary that sound itself undergoes few or no variations in time. For this reason this research uses sound signals and sound materials that are as static in time as possible. The more static they are, the more dynamic and important are the consequences of their movement in space, especially for the perception of sound attribute, rhythm, and texture variations

studied in this thesis.

For this purpose, the experiments and compositions present two differentiated sound materials. On one hand, short sound structures represent the gestural sound materials, which are differentiated between attacks, gestures, and sound objects depending on their duration. On the other hand, the textural sound materials are characterized by long sound structures, which are divided between sustained tones, continuums, and textures depending on their temporal and formal organization. All these sound materials are organized in space following different relative and absolute positions, as well as sound-space densities.

The experiments show that the most successful sound materials are textural; these are used in the compositions *Polyphonic Continuum* and *Musical Situation 1*. Using gestural sound materials, for instance, implies that the musical discourse is based on constant variations in sound signals, frequencies, note durations, and relative and absolute distances. Sound material is therefore too dynamic, masking to a great extent the perception of sound attribute, rhythm, and texture variations occurring as functions of sound location and sound-space density variations. This is the case of the composition *Topos*.

However, even using textural sound materials, sound location and sound-space density variations are not enough to create interesting musical discourses, at least for long periods of time, because both sound signals and sound materials are too static and their timbre too simple, predictable, and monotonous. In order to invigorate them, it is necessary to incorporate variations on other parameters such as amplitude. In contrast to frequency and timbre variations, amplitude variations do not mask the perception of sound attribute, rhythm, and texture variations produced by sound location and sound-space density variations. The compositions presented here show how important amplitude variations together with sound location and sound-space density variations are, as they provide endless tone color, and timbre variations to the same sound signals and sound materials.

The most important characteristic of such sound attribute, rhythm, and texture variations is that they are functions of space, not created a priori but resulting from the spatialization of the notes in the 8-note groups. As a result of this dependence, the listener perceives cause-effect relations between sound movement and sound attribute, rhythm, and texture variations. The perception of this dialog represents the most important feature of the compositions presented in this thesis.

In addition, this thesis shows the importance of spatial position and spatial extension. In *Polyphonic Continuum*, for instance, the first five polyphonic situations are repeated identically, with the exception of a different spatialization for each continuum, i.e. from one area to another area or circle. In this sense, the change from a spatial extension of an area to a circle has a special influence on the sound-space density of each continuum, providing enough variation for the same exact sound material to present new sound attribute, rhythm, and texture variations.

Together with the perception such variations, the listener perceives recognizable sound trajectories associated with variations in the position and sound-space density of the sound material, which permits the molding of sound in space creating dialogs between different sound movements, velocities, and sound directions, and perceiving a spatial relief.

Besides sound movement, the separation of sounds in space permits the differentiation of simultaneous sound materials and the creation of dialogs between them. In this sense, the principle of no overlapping, which prevents different sound materials from occupying the same space at the same time, functions very well to provide sound clarity and sound transparency to the musical discourse.

This thesis shows that sound spatialization can be related to the micro and macro structures of a composition to such an extent that the musical discourse can no longer be perceived without the use of space. As soon as space is used to determine the form of sound, it becomes a fundamental parameter of the perception of sound, and of music. In this sense, this thesis aims to take sound spatialization a step further, by presenting three compositions that put these new possibilities of sound spatialization into practice.

There is much left to explore; the importance of this approach to spatialization in musical composition must be further evaluated. Further projects in this research will aim to determine if the strategy presented in this thesis is relevant to a wide variety of compositions and musical discourses beyond the ones presented here, and to discern whether this investigation has reached an ending point or not. For this reason, it is necessary to investigate with other sound signals and sound materials, and to find more formal relations between sound and space that can enrich the perception of sound and music. In this sense, this research can clearly be further developed. Another possibility would be to start from relations between sound and acoustic space in order to extend the

limits of our perception. Independently of the importance of these findings, under a personal and artistic perspective, this thesis allowed me to discover new musical situations that were completely unthinkable six years ago.

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GLOSSARY OF TERMS

Absolute distance: temporal distance between the 8-note groups.

Absolute position: temporal and spatial organization of the notes in the 8-note groups using all possible sound-space densities, from 8/1 to 8/8.

Principle of no overlapping: the principle by which simultaneous 8-note groups, attacks, gestures, sound objects, textures, continuums, or sustained tones are radiated through areas and circles without using the same loudspeakers. For the principle of no overlapping to be satisfied, a loudspeaker cannot radiate simultaneously two or more sound materials; as both areas and circles share the same sound sources, the sound sources used to radiate a sound material through one circle are not used for the sound material played in the areas occurring at the same time. In this case, the number of loudspeakers available in the areas is reduced.

Relative distance: temporal distance between the notes in the 8-note groups.

Relative position: temporal and spatial organization of the notes in the 8-note groups using always sound-space density 8/8, and absolute position 1234-5678.

Sound-space density: the amount of loudspeakers used to radiate the 8-note groups. As the loudspeakers are spread in space, the number of loudspeakers used to radiate the 8-note groups defines the spatial extension of the notes in the 8-note groups, and the distance and separation between them.

APPENDIX I: Additional Figures

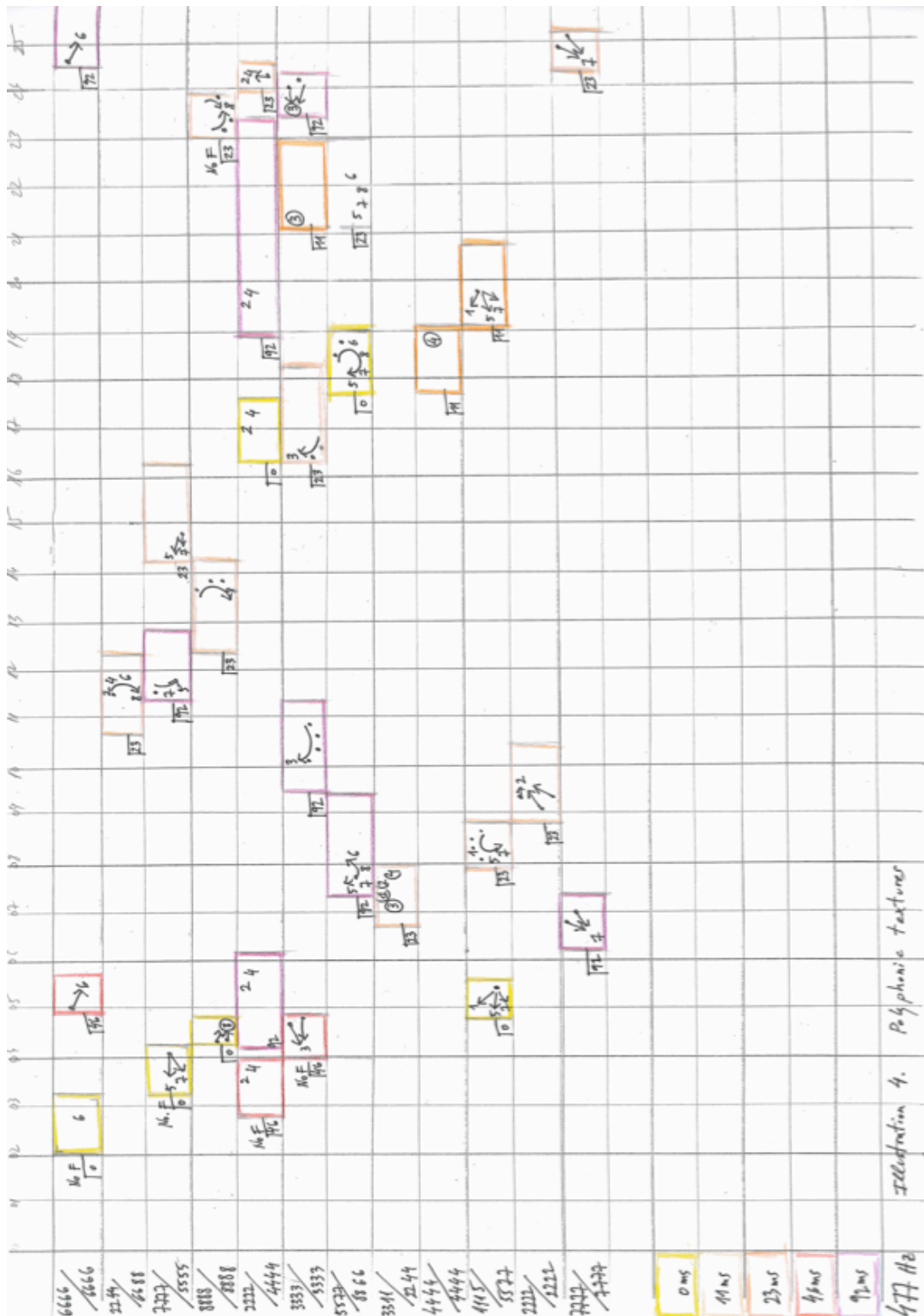


Figure 90. Polyphonic texture corresponding to test 4.4.4.

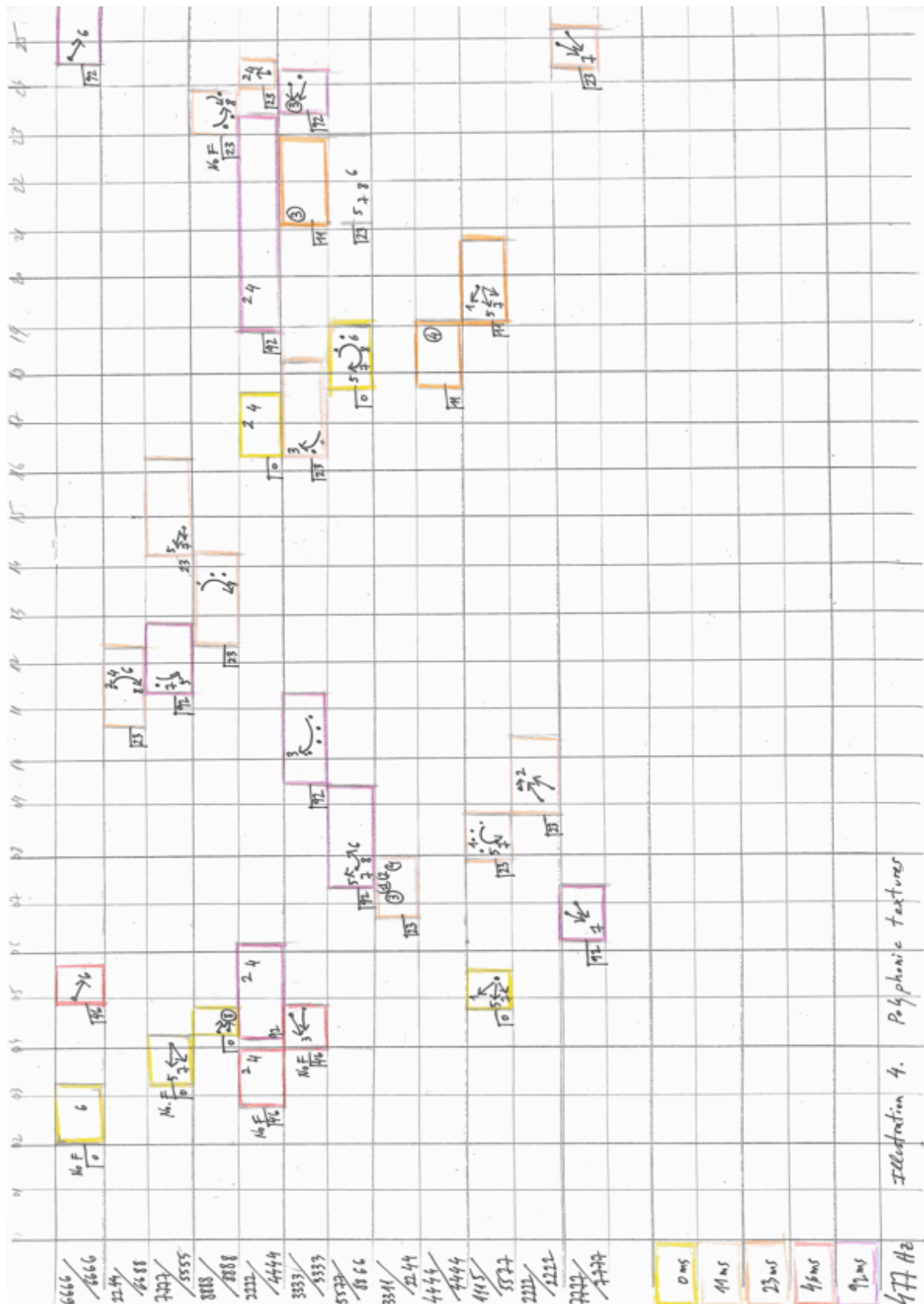


Figure 91. Polyphonic texture corresponding to test 4.4.5.

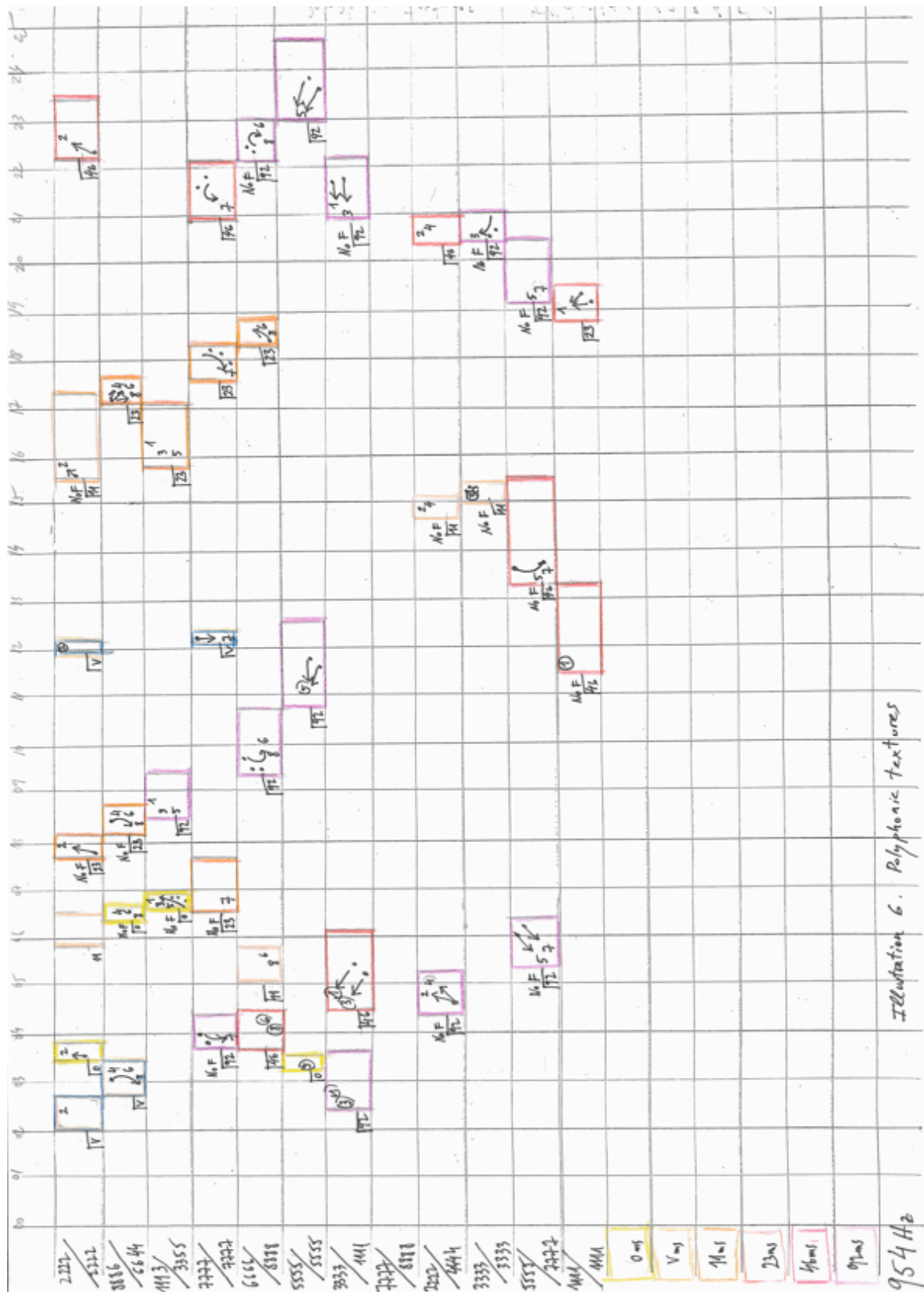


Figure 92. Polyphonic texture corresponding to test 4.4.6.

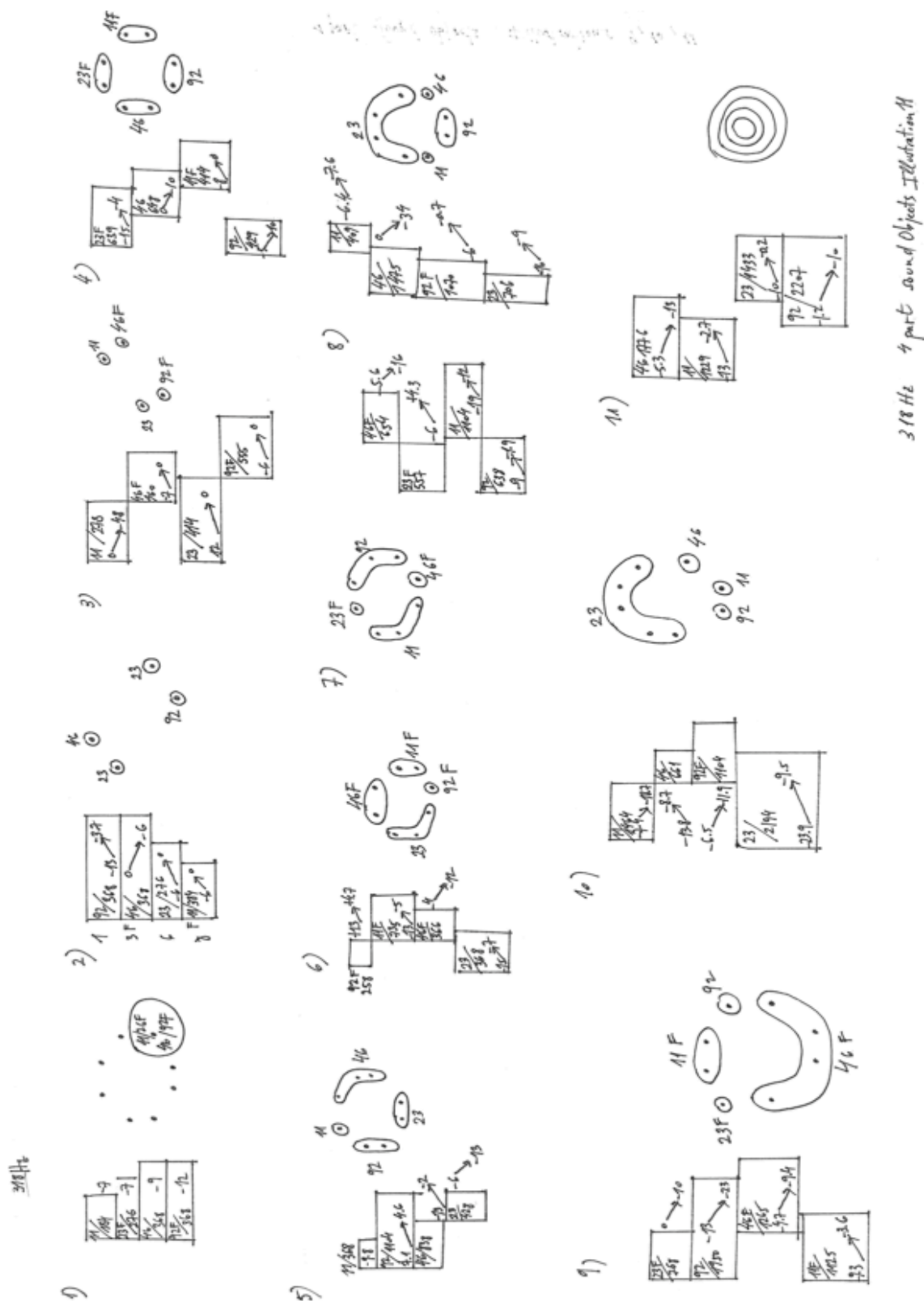


Figure 93. Graph of the spatial and temporal organization for each sound object corresponding to test 5.1.3.

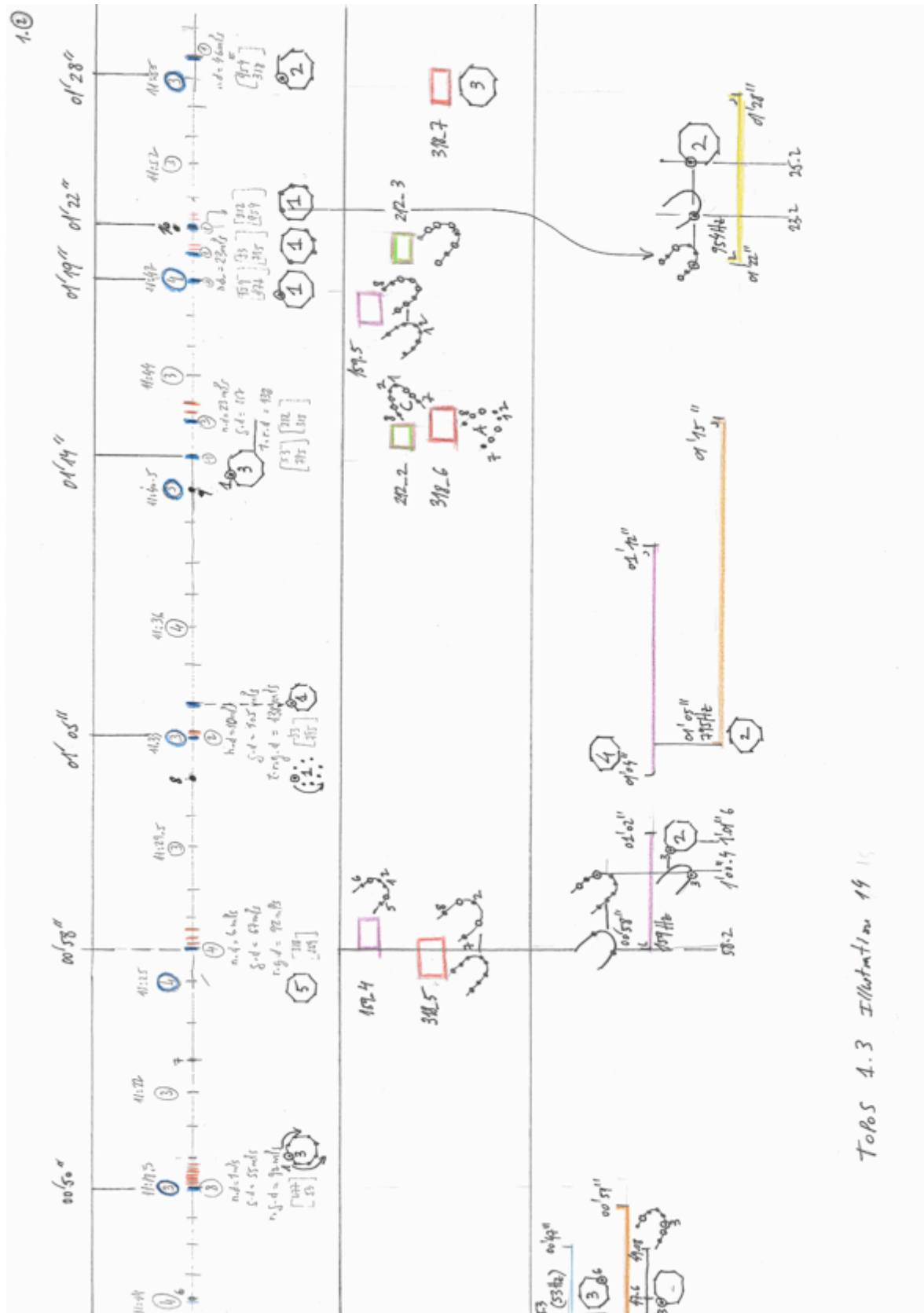
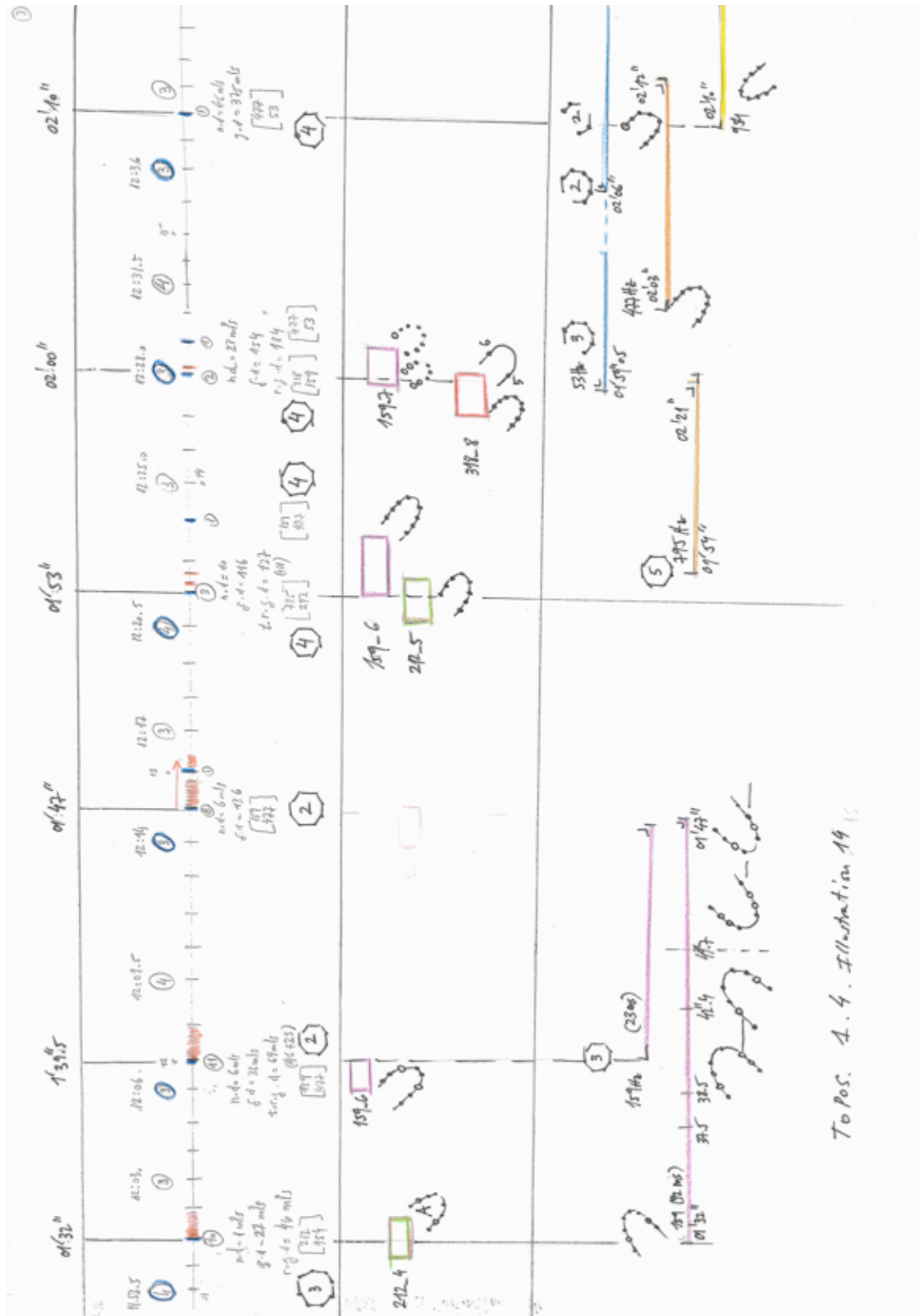


Figure 94. Graphic score of the piece *Topos* (page 2 of 4)



Topos. 4.4. Illustration 14

Figure 95. Graphic score of the piece *Topos* (page 3 of 4)

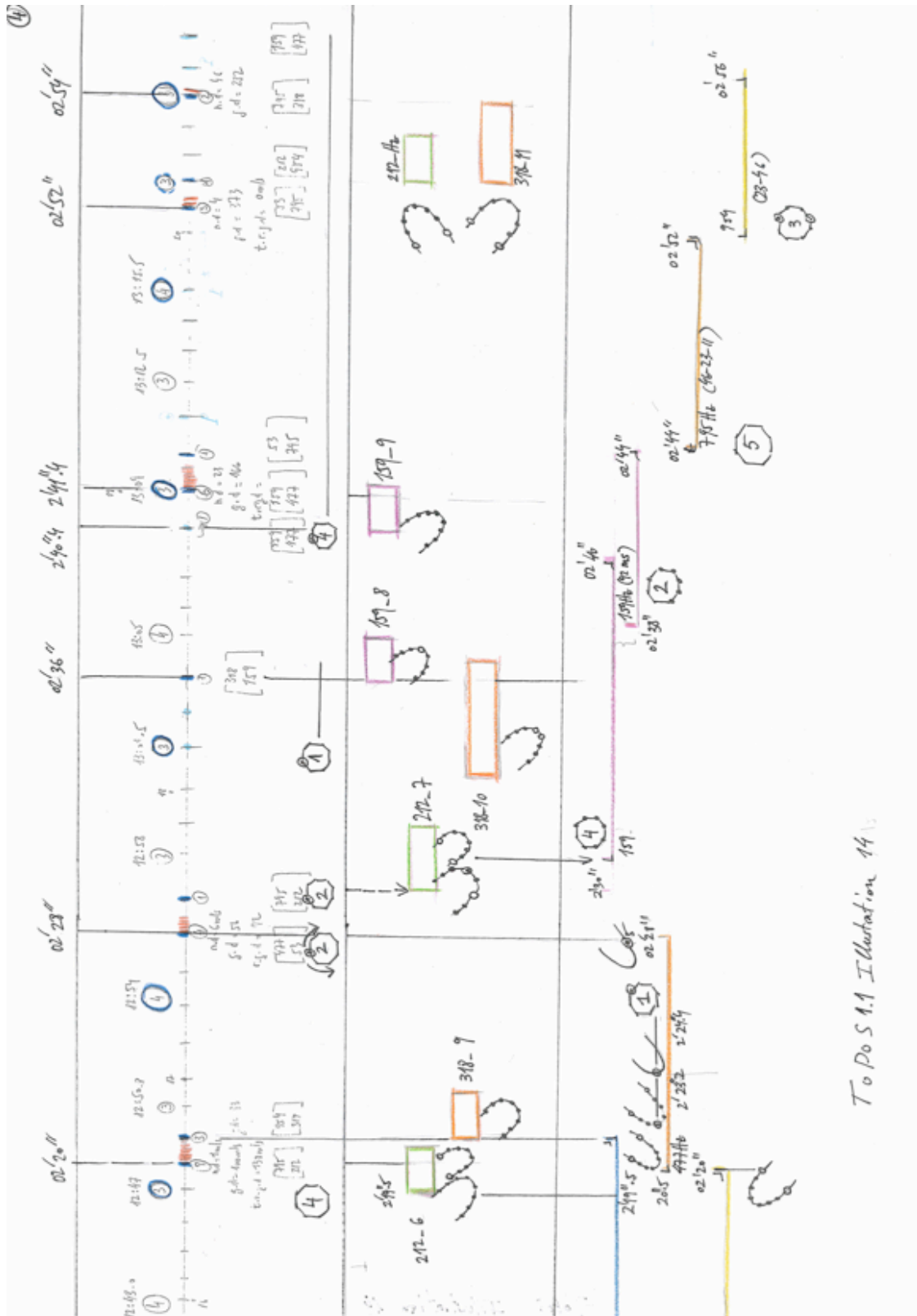


Figure 96. Graphic score of the piece *Topos* (page 4 of 4)

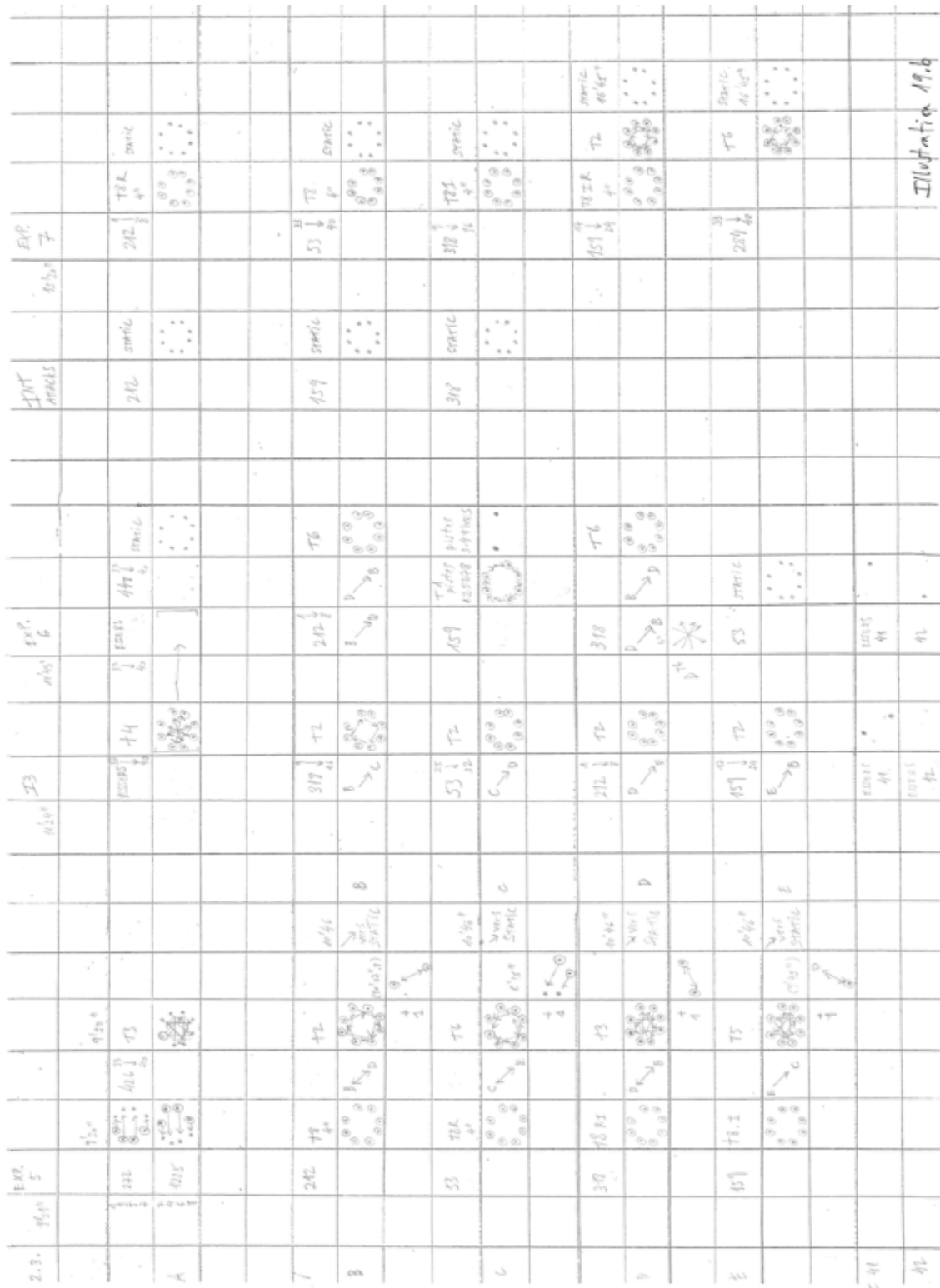


Figure 97. Graphic score of *Musical Situation 1* showing the movement of the notes in the 8-note groups for each sustained tone (page 2 of 3).

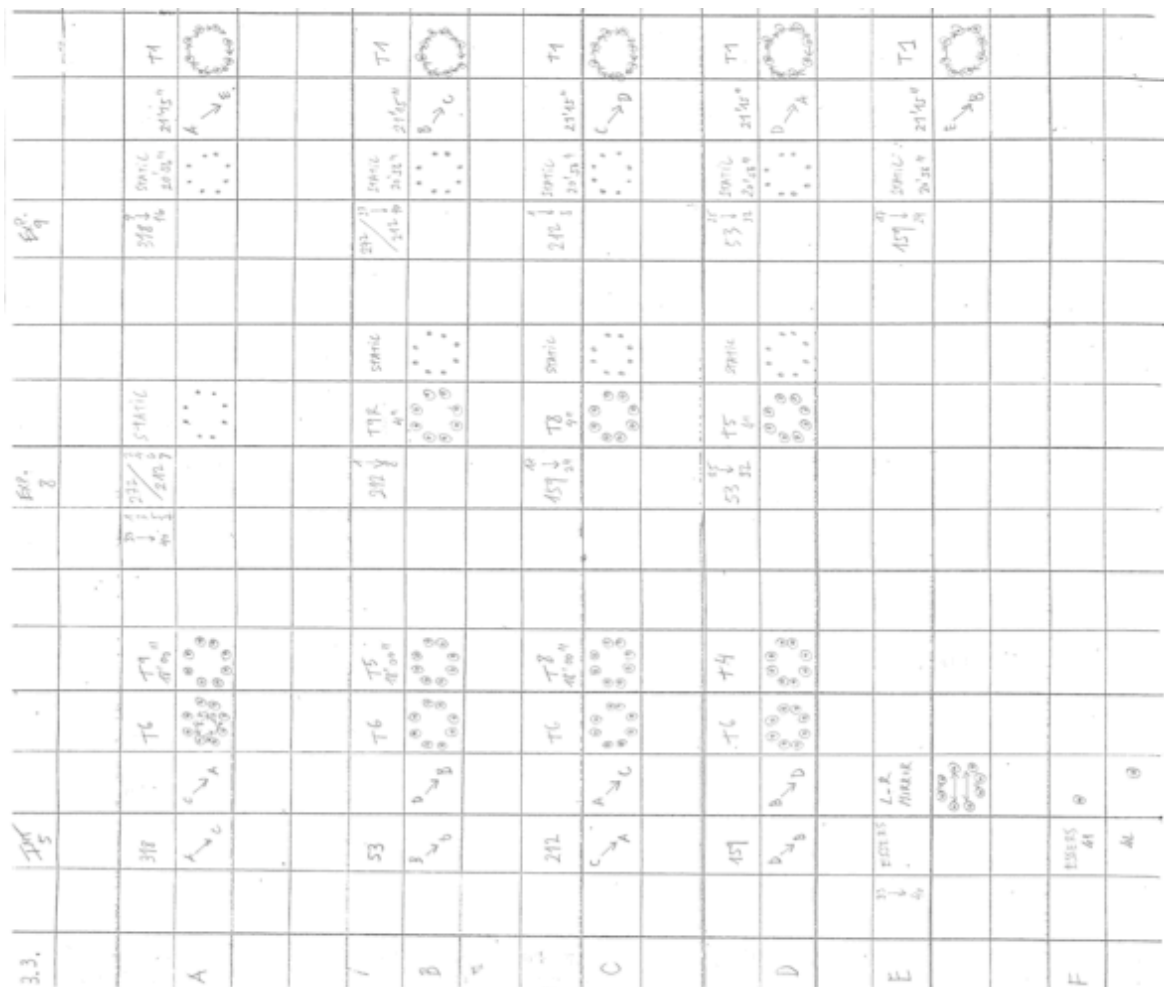


Figure 98. Graphic score of *Musical Situation 1* showing the movement of the notes in the 8-note groups for each sustained tone (page 3 of 3).

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Organization and Description of the Experiments

The research is based on a series of experiments, each one containing several tests. The experiments are organized according to the type of sound material they use, so they are divided into five groups: 8-note groups, sustained tones, attacks, textures, and sound objects. Each experiment evaluates the corresponding sound material in relation to its efficiency to produce the perception of sound attribute, rhythm, and texture variations produced by sound localization and sound-space density variations.

Experiment 1 uses only one frequency and contains 6 tests, which investigate to what extent sound localization influences the perception of pitch, loudness, and tone color variations. The first three tests evaluate and describe the perception of these sound attribute variations using 8-note groups with a frequency of 408 Hz and different note durations and sound signals. Test 1.1 uses sine waves, test 1.2 triangle waves, and test 1.3 short impulse (3 ms) sine waves. These tests show that when using sine waves and triangle waves, pitch, loudness, and tone color variations are indeed perceived although they are very subtle. Therefore, other sound signals with more complex and variable spectra are omitted from both the following tests and the compositions included in part 2.

As it is noticed that using short note durations the perception of both front and rear sound locations diminish in relation to the ones at the sides, test 1.4 is an attempt to improve sound localization by (1) increasing the amplitude levels of the front and rear sound signals in relation to the others, and (2) adding the transient sounds produced when removing the fade-in and fade-out envelopes of each note in the 8-note groups. The first option is dismissed because changing the amplitude variations between the notes in the 8-note groups creates rhythmic patterns that mask the perception of sound attribute variations, especially when using short note durations. The second option is used often throughout the compositions.

Test 1.5 investigates to what extent relative position variations confer dynamism to the 8-note groups, while test 1.6 evaluates the dynamism achieved by using simultaneous relative and absolute position variations, which was determined to be much more efficient than the previous test in which only relative position variations were used.

The tests included in experiment 2 focus on sustained tones, and to what extent

relative position variations are able to confer sufficient sound dynamism, i.e. sound position and sound attribute variations. In the case of sustained tones, sound-space density is limited to 8/8, and no other sound-space densities or absolute positions are used. The conclusion states that relative position variations proved to be sufficient when accompanied by smooth and gradual amplitude variations, as it is shown in the composition *Musical Situation 1*. The amplitude variations are very important to the creation of diffuse sound fields characteristic of this sound material and sound spatialization.

Experiment 3 continues the research on sound perception and sound localization undertaken in experiment 2 using short 8-note group impulses (attacks). As tests 1.3, 1.5, and 1.6 show that the attacks created using 8-note groups with the same frequency through different relative and absolute positions are not dynamic enough as they are not perceived with enough sound attribute and sound position variations, test 3.1 uses 5-note groups with five different frequencies. Even though the use of different frequencies masks the perception of sound attribute variations, they create a more dynamic situation because the 8-note groups are more differentiated from one another, which also improves sound localization. Test 3.2 is an attempt to achieve further dynamism in relation to sound localization by using the so-called “left-right space dilation absolute position rows”, which imply the alternation of the left-right hemispheres, together with the sound dilation from one sound source to several sound sources. The left-right space dilation absolute position rows proved to be very successful and they are used in the piece *Topos*, as they supply sound clarity and transparency to the 5-note groups.

Experiment 4 uses textural sound materials, and contains five tests. Test 4.1 evaluates to what extent relative positions alone create dynamic textures compared to simultaneous relative and absolute position variations, proving that relative position variations alone cannot create enough sound attribute and sound localization variations to be considered dynamic. Test 4.2 evaluates how the sum of relative and absolute position variations are able to create long, homogeneous textures using the same sound signal, frequency, note duration, and relative and absolute distances through relative and absolute position variations, and it shows that they are perceived with important sound attribute, rhythm, textures, sound-space density, and sound location variations. These textures are called continuums, which permit, for the first time, to perceive the dialog between sound

perception and sound spatialization. This dialog helps produce an interesting and dynamic musical situation. The continuums are used in the piece *Polyphonic Continuum*. Test 4.3 produces several textures using the same frequency and note durations but different relative and absolute distances for each texture, showing the importance of these parameters to the creation of irregular (rough) or even (smooth) textures. Additionally, in contrast to continuums, two differentiated sound qualities are used in the same texture, which result from using sounds with or without fade-in and fade-out envelopes. These textures are used to create the sound objects (experiment 5) employed in the composition *Topos*, as well as to create polyphonic and double polyphonic textures used in tests 4.4 and 4.5. Test 4.4 presents polyphonic textures, which are produced using the same textures with the same frequency (but different note durations and relative and absolute distances) as test 4.3, and evaluates whether or not it is possible to perceive the dialog between sound perception and sound spatialization as occurred with the continuums. It shows that when using textures with different relative and absolute distances, such a dialog is not perceived, as it is not possible to differentiate each texture from the others. Instead, what is perceived is the same texture through different densities. Test 4.5 creates double polyphonic textures using the same polyphonic textures in test 4.4, and evaluates if the use of polyphonic textures with different frequencies permits better differentiation of the textures from one another and better perception of the dialog between sound and space. In both cases, the cause-effect relation is not perceived, so neither the polyphonic textures nor the double polyphonic textures are used in any of the compositions presented in part 2.

Experiment 5 uses short portions of the textures created in test 4.3 to produce short sound objects, and contains two tests. Test 5.1 evaluates sound attribute and texture variations produced by relative and absolute position variations of short sound objects using textures with the same frequency. Even though the dialog between sound and space is nonexistent, these sound objects are used in the piece *Topos*. The reason is that they are understood as extensions of the attacks, and, instead of sound attribute, rhythm, or texture variations, they create dynamic variations in relation to sound localization. Test 5.2 is a further attempt to perceive sound attribute variations through the creation of longer sound objects. Unlike the previous tests, test 5.2 creates longer sound objects by repeating each texture two to several times through different absolute positions with different sound-space densities, and combining different sound signal types, i.e. sine waves and triangle waves.

These long sound objects proved to be dynamic because they change constantly the sound parameters, although they are not used in any of the compositions because the dialog between sound attribute, rhythm, and texture variations involved in each sound object is, similarly to the previous test, not perceived.

An audio file accompanies each experiment to be found in the DVDs 1 and 2 included in appendix III. Each DVD contains Pro Tools sessions with the same name as the tests. The time indication that appears next to each test indicates the beginning and end of each individual test in relation to the corresponding Pro Tools session.

Experiment 1: tests on the perception of sound attribute variations related to sound localization using 8-note groups.

Test 1.1: 8-note Groups with Sine Waves.

Objectives:

- 1) to evaluate and describe the auditory events concerning the perception of sound attribute variations of a sine wave radiated from eight different directions in relation to the ears, using eight loudspeakers arranged around the listener following the approximate shape of a regular octagonal (see figure 16, p. 67). Each test uses groups of eight notes (8-note-groups) with the same sound signal, frequency, note duration, amplitude, relative distance, and relative position.
- 2) to evaluate and describe the auditory events concerning sound localization.

Test 1.1.1 (time: 00' 01'')

Static 8-note groups. No position changes.

Sound signal: SINE WAVE

Phase of the sine wave for each note: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Relative distance: ± 1000 ms

Sound sources: 1 SOURCE

Observations on sound perception: the 8-note groups are perceived with no sound

attribute variations.

Test 1.1.2 (time: 00' 15'')

Sound signal: SINE WAVE

Phase of the sine wave for each note: VARIABLE

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Relative distance: ± 1000 ms

Sound sources: 1 SOURCE

Observations on sound perception: using sound signals with variable phase (τ_{ph}), the 8-note groups are perceived with no sound attribute variations.

Test 1.1.3 (time: 00' 28'')

Sound signal: SINE WAVE

Phase of the sine wave for each note: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Relative distance: 0 ms

Sound sources: 8 SOURCES

Observations on sound perception: variations in pitch, loudness and tone color are perceived.

Observations on sound localization: there is a predominance to localize the auditory events at the left-right and front hemispheres. Sound localization diminishes sounds situated at the rear (sound sources 7 and 8). Sound sources 3-5 and 4-6 are not differentiated, as they are perceived as one unique left-right position. In general, sound localization is blurred.

Test 1.1.4 (time: 00' 37'')

Sound signal: SINE WAVE

Phase of the sine wave for each note: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Relative distance: 0 ms

Sound sources: 8 SOURCES

Observations on sound perception: no differences in sound perception compared to the previous test using sound signals with IDENTICAL phase.

Observations on sound localization: no differences in sound location compared to the previous example using sound signals with IDENTICAL phase.

Test 1.1.5 (time: 00' 50" / 01' 02" / 01' 32")

Sound signal: SINE WAVE

Phase of the sine wave for each note: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Relative distance: First example: 0 sec.

Second example: 1 to 3 sec.

Third example: 3 to 6 sec.

Sound sources: 8 SOURCES

Observations on sound perception: while the relative distance increases, the perception of pitch and tone color become more attenuated. Only changes in loudness are clearly perceived.

Observations on sound localization: while the relative distance increases, the attention focuses on sound localization. A good perception of sound attribute variations is inversely proportional to the increase of the relative distance.

Test 1.1.6 (time: 02' 20" / 02' 29" / 02' 38")

Objective: to evaluate and compare the perception of sound attribute variations when the notes in the 8-note groups 1) alternate the left-right/ front-rear displacements, 2) first 4 left, last 4 right, and 3) mixed displacements front-rear and left-right.

Sound signal: SINE WAVE

Phase of the sine wave for each note: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Relative distance: 0 ms

Sound sources: 8 SOURCES

Relative Position:

First example: 1-2-3-4/5-6-7-8 (alternation of left-right/ front-rear)

Second example: 1-3-5-7/ 2-4-6-8 (first 4 left, last 4 right, always front-rear)

Third example: 1-7-3-8-5-2-7-4 (mixed displacements front-rear and left-right)

Observations on sound perception: although all the examples are very similar, in order to perceive more tone color and amplitude variations, sound trajectories that alternate simultaneous left-right/front-rear trajectories are more efficient, as in the third example.

Test 1.1.7 (time: 02' 49" / 03' 00" / 03' 21")

Objective: to evaluate the perception of sound attribute and sound localization variations while increasing the note durations of the notes in the 8-note groups.

Sound signal: SINE WAVE

Phase of the sine wave for each note: IDENTICAL

Frequency: 408 Hz

Note duration: 1000 ms

Amplitude: CONSTANT (-15 dB)

Relative distance: 0 ms

Sound sources: 8 SOURCES

Observations on sound perception: increasing the note durations, the perception of sound quality variations remains invariable.

Observations on sound localization: increasing the note durations, sound localization is reinforced.

Test 1.1.8 (time: from 03'51" / 04'11" / 04'17" / 04'21" / 04'25" / 04'28" / 04'31" / until 04'32")

Objective: to evaluate the perception of sound attribute variations and sound localization while decreasing the note duration of the notes in the 8-note groups.

Sound signal: SINE WAVE

Phase of the sine wave for each note: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms / 500 ms / 250 ms / 125 ms / 65 ms / 30 ms / 15 ms

Relative distance: 0 ms

Sound sources: 8 SOURCES

Observations on sound perception: Using 8-note groups with a note duration of 1000, 500 and 125 ms, sound attribute variations remain equally perceptible until 125 ms.

By decreasing the note duration, the perception of sound attribute variations tends to disappear. With note duration of 65 ms, only 5 of the 8 notes in the 8-note-groups are perceived, and with one unique pitch, loudness and tone color.

With note duration of 30 ms, only 4 of the 8 notes in the 8-note-groups are perceived, and with one unique pitch, loudness and tone color.

With note duration of 15 ms, the 8-note groups are perceived as two impulses (attack and echo). The notes are not perceived with a definite pitch anymore, but with a mixture of pitch and non-pitch.

Observations on sound location: From 1000 ms until 125 ms, sound location is well perceived. With 65 ms, sound localization become limited to left-right aural hemispheres. With 30 and 15 ms, depending on the positions of the first and last events, the localization is focused toward one or two positions (always left-right).

CONCLUSIONS:

1. One identical sound signal (408 Hz sine wave) is perceived with sound attribute variations when radiated from different positions.
2. Moving the sound through the left-right hemispheres seem to create more contrasting sound attribute variations.
3. While decreasing sound duration (thus increasing the speed of movement), sound attribute variations tend to disappear.
4. Decreasing the duration from 60 ms on, the perception of the sound sources situated behind tends to disappear. With 15 ms only front-left and front-right positions are perceived.
5. With note durations of 1000, 500 and 250 ms, the notes in the 8-note groups are perceived individually. From 125 ms on, the 8-note groups are perceived as one attack followed by reflections or echoes.
6. It is impossible to control the type of sound attribute variations in relation to their position. Left-right position changes seem to be more satisfactory, although it is difficult to determine to which extent, as sound attribute variations depend directly on how different

they are perceived in relation to the previous event. Memory cannot remember sound attribute variations of each individual note, and only the ones that occur with two consecutive notes can be perceived.

7. The experiments show that the speed of movement increases, sound localization focuses on the left-right hemispheres while the qualitative perception of sounds tend to be more homogeneous. As soon as the pitches in the 8-note groups are perceived as one impulse, the position and sound attributes of both the first and last notes seem more important than the rest.

Test 1.2: 8-note Groups with Triangle Waves.

Objectives:

1. Evaluate and describe the auditory events concerning the perception of sound attribute variations using a sound signal with multiple partials (triangle wave) from eight different directions in relation to the ears, using eight loudspeakers arranged around the listener following the approximate shape of a regular octagonal (see figure 16 p. 66), and compare the results with the previous test 1.1. Similarly to test 1.1, each test uses groups of eight notes (8-note-groups) with the same frequency, note duration and amplitude, relative distance and relative position.

2. Evaluate and describe the auditory events concerning sound localization and compare the results with the previous test 1.1.

Test 1.2.1 (time: 00' 01'')

Static 8-note groups. No position changes.

Sound signal: TRIANGLE WAVE

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Relative distance: 1000 ms

Sound sources: 1 SOURCE

Observations on sound perception: the 8-note groups are perceived with no sound attribute variations.

Test 1.2.2 (time: 00' 15'')

Sound signal: TRIANGLE WAVE
Phase of the sine wave for each repetition: VARIABLE
Frequency: 408 Hz
Amplitude: CONSTANT (-15 dB)
Note duration: 1000 ms
Relative distance: 1000 ms
Sound sources: 1 SOURCE

Observations on sound perception: using sound signals with variable phase (τ_{ph}), the 8-note groups are perceived with no sound attribute variations.

Test 1.2.3 (time: 00' 28'')

Sound signal: TRIANGLE WAVE
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz
Amplitude: CONSTANT (-15 dB)
Note duration: 1000 ms
Relative distance: 0 ms
Sound sources: 8 SOURCE

Observations on sound perception: for each position, variations in pitch, loudness and tone color are perceived, similar to the ones using sine waves.

Observations on sound localization: in comparison to test 1.1, sound localization from behind (channels 7-8) is better. In addition, sound localization is improved for sound sources 3-5 and 4-6, as with triangle waves they are more differentiated.

Test 1.2.4 (time: 00' 37'')

Sound signal: TRIANGLE WAVE
Phase of the sine wave for each repetition: VARIABLE
Frequency: 408 Hz
Amplitude: CONSTANT (-15 dB)
Note duration: 1000 ms
Relative distance: 0 ms
Sound sources: 8 SOURCES

Observations on sound perception: same as the test using sine waves, no differences

in sound perception compared to the previous test using sound signals with IDENTICAL phase barely perceived.

Observations on sound location: same as the test using sine waves, no differences in sound location compared to the previous example using sound signals with IDENTICAL phase are perceived.

Test 1.2.5 (time: 00' 50" / 01' 02" / 01' 32")

Sound signal: TRIANGLE WAVE

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Sound sources: 8 SOURCES

Relative distance: First example: 0 sec.

Second example: 1 to 3 sec.

Third example: 3 to 6 sec.

Observations on sound perception: as with sine waves, when the relative distance is increased the perception of pitch and tone color variations become more attenuated. Only changes in loudness are clearly perceived.

Observations on sound location: as with sine waves, increasing the relative distance causes the attention to focus on sound localization. Perception of sound attribute variations is inversely proportional to the increase of the relative distance.

Test 1.2.6 (time: 02' 20" / 02' 29" / 02' 38")

Objective: to compare and evaluate the perception of sound attribute variations when the notes in the 8-note groups (1) alternate the left-right/ front-rear displacements, (2) occupy first 4 left, last 4 right, and (3) undergo mixed displacements front-rear and left-right.

Sound signal: TRIANGLE WAVE

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms

Sound sources: 8 SOURCES

Relative distance: 0 ms

Relative Position:

First example: 1234-5678 (alternation of left-right/ front-rear)

Second example: 1357-2468 (first 4 left, last 4 right, always front-rear)

Third example: 1738-5274 (simultaneous front-rear and left-right)

Observations on sound perception: as with sine waves, although all the examples are very similar, sound trajectories that alternate simultaneous left-right/ front-rear trajectories are more efficient for the perception of tone color and amplitude variations.

Test 1.2.7 (time: 02' 49" / 03' 00" / 03' 21")

Objective: to evaluate the perception of sound attribute and sound localization variations while increasing the durations of the notes in the 8-note groups.

Sound signal: TRIANGLE WAVE

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Note duration: 1000 ms

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms / 2000 ms / 3000 ms

Sound sources: 8 SOURCES

Relative distance: 0 ms

Observations on sound perception: as with sine waves, when the note durations are increased the perception of sound quality variations remains invariable.

Observations on sound location: as with sine waves, increasing note durations reinforces sound localization.

Test 1.2.8 (Time: 03'51"/ 04'11"/ 04'17"/ 04'21"/ 04'25"/ 04'28"/04'31"/ and 04'32")

Objective: to evaluate the perception of sound attribute variations and sound localization while decreasing the note duration of the notes in the 8-note groups.

Sound signal: TRIANGLE WAVE

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 1000 ms / 500 ms / 250 ms / 125 ms / 65 ms / 30 ms / 15 ms

Sound sources: 8 SOURCES

Relative distance: 0 ms

Observations on sound perception: as with sine waves, when using 8-note groups with note durations of 1000, 500, and 125 ms, sound attribute variations remain equally perceptible until 125 ms.

By decreasing the note duration, the perception of sound attribute variations tends to disappear. With note duration of 65 ms, only five of the notes in the 8-note-groups are perceived, and with one unique pitch, loudness, and tone color.

With note duration of 30 ms, only four of the notes in the 8-note-groups are perceived, and with one unique pitch, loudness and tone color.

With note duration of 15 ms, the 8-note groups are perceived as two impulses (attack and echo). The notes are no longer perceived with a definite pitch, but with a mixture of pitch and non-pitch.

Observations on sound location: similar to sine waves. From 1000 ms until 125 ms, sound locations are well perceived. With 65 ms, sound localization is limited to left-right hemispheres only. With 30 and 15 ms, depending on the positions of the first and last events, localization is focused on one or two positions (always left-right).

CONCLUSIONS:

- 1) Using sounds with multiple partials attenuates the perception of sound attribute variations compared to sine waves.
- 2) The perception of sound attribute variations is inversely proportional to relative distance.
- 3) Sound sources 3-5 and 4-6 seem to be more differentiated compared to sine waves. This experience coincides with the theory that broadband ear input signals contain more information about the position of the sound source narrow band signals.¹⁹⁸ This would explain why sound localization of sine waves is less clear, and why sound localization is of triangle waves is more clear.

¹⁹⁸ Blauert, 1997, p.101.

Test 1.3: 8-note Groups with Note Durations of 3 m.

Objectives:

- 1) to evaluate and describe auditory events concerning the perception of sound attribute variations when 8-note groups with a note duration of 3 ms are radiated from eight different locations in space (see figure 16, p. 66). In this test the notes in the 8-note groups use sound signals with or without fade-in and fade-out envelopes.
- 2) to evaluate and describe auditory events concerning sound localization.

Test 1.3.1 (time: 00' 01'')

Static sound. No position changes.

Sound signal: TRIANGLE WAVE

FADES: the first three examples include fade-in and fade-out envelopes;
the next three do not.

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (0 dB)

Note duration: 3 ms.

Relative distance: 1000 ms.

Sound sources: 1 SOURCE

Observations on sound perception: the notes in the 8-note groups are perceived with no sound attribute variations.

Test 1.3.2 (time: 00' 15'')

Sound signal: TRIANGLE WAVE

FADES: the first two examples include fade-in and fade-out envelopes;
the next two do not.

Phase of the sine wave for each repetition: VARIABLE

Frequency: 408 Hz

Amplitude: CONSTANT (0 dB)

Note duration: 3 ms.

Relative distance: 1000 ms.

Sound sources: 1 SOURCE

Observations on sound perception: using sound signals with variable phase (τ_{ph}), the notes in the 8-note groups are perceived with no sound attribute variations.

Test 1.3.3 (time: 00' 28'')

Sound signal: TRIANGLE WAVE
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz
Amplitude: CONSTANT (0 dB)
Note duration: 3 ms.
Relative distance: 1000 ms.
Sound sources: 8 SOURCES

Observations on sound perception: in each position the notes in the 8-note groups are perceived with no substantial pitch, loudness, or tone color variations. They are perceived as almost identical, with insignificant differences between left-right sound sources.

Observations on sound location: sound localization is improved using short sound impulses, as sounds from the rear are more recognizable compared to tests 1.1 and 1.2. However, sound sources 3-5 and 4-6 are not completely differentiated, and their localization remains blurred.

Test 1.3.4 (time: 00' 37'')

Sound signal: TRIANGLE WAVE
Phase of the sine wave for each repetition: VARIABLE
Frequency: 408 Hz
Amplitude: CONSTANT (0 dB)
Note duration: 3 ms.
Relative distance: 1000 ms.
Sound sources: 8 SOURCES

Observations on sound perception: the perception of sound attribute variations is produced by differences in phase more than sound localization. This test uses two sounds with different phases, and only two important sound attribute variations are perceived.

Observations on sound location: good sound localization, same as with IDENTICAL phase.

Test 1.3.5 (time: 00' 50'' / 01' 02'' / 01' 32'')

Sound signal: TRIANGLE WAVE
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz
Amplitude: CONSTANT (0 dB)

Note duration: 3 ms.

Relative distance: 1 sec. / 1 to 3 sec. / 3 to 6 sec.

Sound sources: 8 SOURCES

Observations on sound perception: increasing the relative distance implies that the perception of pitch and tone color variations, which are already unimportant using shorter relative distances, disappear almost completely when they reach a relative distance of 3 to 6 seconds. Only small changes in loudness are perceived.

Observations on sound localization: as soon as the perception of sound attribute variations disappears together with the increase of the relative distance, all the attention focuses on sound localization.

Test 1.3.6 (time: 02' 20" / 02' 29" / 02' 38")

Objective: to experiment with different left-right-front-rear sound trajectories to find out which ones reinforce the perception of sound attribute variations.

Sound signal: TRIANGLE WAVE

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (0 dB)

Note duration: 3 ms.

Relative distance: 1000 ms.

Relative Position: First example 1234-5678 (left-right alternation)

Second example 1357-2468 (first 4 left, last 4 right)

Third example 1738-5274 (simultaneous front-rear, left-right)

Sound sources: 8 CHANNEL

Observations on sound perception: no substantial differences compared to the previous test 1.1 and 1.2.

Test 1.3.7 (time: from 02' 51" / 03' 11" / 03' 17" / 03' 21" / 03' 25" / 03' 28" / 03' 31" / until 03' 32")

Objective: to experiment with different relative distances to determine which ones reinforce the perception of sound attribute variations.

Sound signal: TRIANGLE WAVE

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (0 dB)

Note duration: 3 ms.

Relative distance: 1000 ms / 500 ms / 250 ms / 125 ms / 65 ms / 30 ms / 15 ms

Sound sources: 8 CHANNEL

Observations on sound perception: with relative distances of 500, 250, and 125 ms, sound attribute variations seem to be better perceived. From 65 ms until 15 ms, one attack followed by more or fewer reflections (or echoes) is perceived, all of them with the same sound quality.

Observations on sound localization: good sound localization until 65 ms. By decreasing the relative distance, fewer notes in the 8-note groups are perceived, and sound localization tends to focus on the left-right hemispheres. With relative distances of 30 and 15 ms, the position of the first and last notes seem to be more important than the rest, and sound localization is limited to the left-right aural hemispheres.

CONCLUSIONS:

- 1) Using sound impulses as 8-note groups with a note duration of 3 ms, sound localization is improved compared to the previous 8-note groups with longer note durations.
- 2) However, the perception of sound attribute variations between the notes in the 8-note groups is not as clear as with longer note durations, although they do exist.
- 3) The perception of the sound attribute variations are more important with relative distances of 500 and 125 ms, as the previous tests using longer note durations. With shorter relative distances, fewer notes in the 8-note groups are perceived, and all of them with one unique sound quality.
- 4) Good sound localization until 65 ms. With shorter relative distances, sound location is perceived only partially, and the relative position of the first and last notes seem to determine the sound localization for the entire 8-note group.
- 5) Using sound impulses the attention focuses on sound localization, as the perception of sound attribute variations is less important. In this sense, it can be stated that the attention prioritizes the perception of sound attributes. When the perception of

sound attribute variations is very active, sound localization becomes less important. As soon as the perception of sound attribute variations is less active, sound localization becomes more important for the listener.

- 6) Different phase relations have a significant influence on the perception of sound attribute variations when using short sound impulses, especially using notes with no fade-ins or fade-outs.
- 7) Front and rear sound sources are better perceived and differentiated when using short note impulses compared to longer note durations.

Test 1.4: 8-note Groups with Front-Rear Amplitude Variations.

Objective: to improve sound localization of sine waves, especially from the front and rear, by varying the amplitude of the sound signals and removing fade-in envelopes, thus creating a transient sound at the beginning of each note in the 8-note groups.

Through the following tests, the same 8-note group is repeated 5 times with the following variations:

- 1) no amplitude variations, all sound sources -15,7 dB
- 2) sound sources 1-2 (front) and 7-8 (behind) + 3 dB
- 3) sound sources 1-2 (front) and 7-8 (behind) + 6 dB
- 4) sound sources 1-2 (front) and 7-8 (behind) + 9 dB
- 5) sound sources 1-2 (front) and 7-8 (behind) + 12 dB

Test 1.4.1 (Time: 00' 01'')

Sound signal: SINE WAVE

Phase of the sine wave for each repetition: VARIABLE

Frequency: 408 Hz

Note duration: 1000 ms

Relative distance: 0 ms

Sound sources: 8 SOURCES

Observations on sound localization: with no amplitude modifications, sound localization is very blurred, especially sound sources 1, 2, 7, and 8.

When the amplitude is increased sound localization remains blurred. Sound localization prioritizes left-right sound sources. Less front sound localization from +9 dB

on. Sound sources 7 and 8, even increasing +12 dB, are still perceived at the front or at the sides. With +12 dB, the amplitude has increased too much and sound is not balanced anymore in relation to the other sound sources.

With a transient noise (click) at the beginning of each note sound is localized more precisely, although the localization of the pitched note after the transient noise remains blurred. Sometimes transient noise and its corresponding pitch are not fully related. Transient sounds are perceived as an independent layer above the pitched notes, which can be related to the sound relief proposed by Schaeffer. Generally, with transient sounds it is possible to better perceive and differentiate the left-right sound sources 3-5 and 2-4, especially when they occur one after the other.

Test 1.4.2 (Time: 01' 47'')

Sound signal: SINE WAVE
Phase of the sine wave for each repetition: VARIABLE
Frequency: 318 Hz
Note duration: 250 ms
Relative distance: 0 ms
Sound sources: 8 SOURCES

Observations on sound localization: same observations as the test 1.4.1. With transient noise at the beginning of each note sound localization is improved, especially for frontal sound sources 1 and 2. By increasing the amplitude, sound sources 7 and 8 tend to be perceived at the front or the sides. Sound localization after the transient sound remains blurred, and sometimes its relation to the corresponding sine wave is not perceived.

Test 1.4.3 (Time: 02' 46'')

Sound signal: SINE WAVE
Phase of the sine wave for each repetition: VARIABLE
Frequency: 318 Hz
Duration: 130 ms
Relative distance: 0 ms
Sound sources: 8 SOURCES

Observations on sound localization: in general, sound localization is blurred. The

perception of left-right sound sources is predominant. Less frontal sound localization, although it is improved by increasing the amplitude at least +9 dB. Sound sources 7 and 8, even when increased by +12 dB, are still perceived at the front or at the sides. With +12 dB, the amplitude has increased too much and sound is not balanced anymore in relation to the other sound sources.

With a transient noise (click) at the beginning of each note sound localization is improved, especially for the frontal sound sources. By increasing the amplitude, sources 7 and 8 are displaced from the front sound localization to the sides. Sound localization of the pitched notes after the transient sounds remains blurred, and sometimes the transient sound is not related to its corresponding note.

Test 1.4.4 (Time: 03' 34'')

Sound signal: SINE WAVE
Phase of the sine wave for each repetition: VARIABLE
Frequency: 318 Hz
Note duration: 130 ms
Relative distance: 0 ms
Sound sources: 8 SOURCES

Observations on sound localization: when the amplitudes of sound sources 1, 2, 7, and 8 are increased, sound localization is improved. Left-right sound localization is more predominant as the speed of movement increases. Sound localization at the front is improved by increasing the amplitude +9 dB. Sound Sources 7 and 8, even increasing +12 dB, are still perceived at the front or at the sides. At +12 dB, the amplitude has increased too much and sound is not balanced anymore in relation to the other sound sources.

Same observations as the previous tests.

Test 1.4.5 (Time: 03' 56'')

Sound signal: SINE WAVE
Phase of the sine wave for each repetition: VARIABLE
Frequency: 318 Hz
Note duration: 130 ms
Relative distance: 0 ms
Amplitude: CONSTANT (-15 dB)

Amplitude changes: Channels 7-8, -4,7 dB

Sound sources: 8 SOURCES

Observations on sound localization: when the amplitudes of sound sources 1, 2, 7 and 8 are increased sound localization is more oriented to the left and right hemispheres. By increasing the speed, i.e. by reducing the note duration of the 8-note groups, amplitude variations fail to improve sound localization of sources 7 and 8 situated at the rear. In general, the notes in the 8-note groups are all perceived at the sides, and increasing the amplitude moves sound localization more to the front.

Perceiving a transient sound at the beginning of each sound: increasing the speed, sound locations are more focused at the left and right. By increasing the speed, increasing the amplitude makes no difference to the perception of sound sources 7 and 8. All is heard at the sides, and by increasing the amplitude the sound moves a little to the front.

CONCLUSIONS:

- 1) In general, using sine waves causes sound localization to remain blurred, no matter the duration of sounds or the changes in amplitude favoring the front and rear sound sources. Trying to improve sound localization by varying the amplitude is ineffective, considering the poor results obtained in the tests.
- 2) The transient sounds at the beginning of the notes in the 8-note groups improve sound localization, although sound localization of the corresponding pitched notes remains blurred.
- 3) Using amplitude changes to emphasize the front and rear sound sources is not recommended. First, because amplitudes can be balanced in relation to a central point, which is in any case the position of the majority of the audience. Second, because different amplitudes create rhythmic patterns in the 8-note groups, which disturb the perception of sound attribute variations.
- 4) Therefore, leaving the volumes equal for every note in the 8-note groups is the best solution, even though sound localization remains blurred, especially sound sources situated at the front and rear.

Test 1.5: 8-note Groups with Relative Position Variations.

Objective: to determine to what extent different relative position variations confer dynamism to the 8-note groups concerning the perception of sound attribute variations.

In order to guarantee maximum dynamism concerning sound movement and the perception of sound attribute variations, sound trajectories in space will follow eight predefined relative positions rows, which potentiate the alternation of the four left-right/front-behind hemispheres (see test 1.5). The eight relative position rows are as follows:

- | | | | |
|----|-----------|----|-----------|
| 1. | 1357-2468 | 5. | 2413-6857 |
| 2. | 4213-6875 | 6. | 7865-1243 |
| 3. | 8756-4312 | 7. | 3618-2754 |
| 4. | 5841-2376 | 8. | 6428-7513 |

Each note in the 8-note group has the same frequency and note duration, appearing always one after the other following the eight relative position rows.

Test 1.5.1 (time 00' 01''/ 00' 26'')

Sound signal: Sine wave

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Sound sources: 8 CHANNEL

Note duration: 250 ms

Relative distance: 0 ms

Absolute distance: VARIABLE (\pm 500-1200 ms)

Observations on sound dynamism: even though sound attribute variations and sound trajectories are perceived differently for each 8-note group, relative position variations are not enough to create a sufficiently dynamic situation. The main reason is that the 8-note groups create a long and regular rhythmic pattern, which is too predictable and static. Pitch, loudness, and tone color variations, while prominent, are not enough to confer interest and dynamism to the 8-note groups.

Test 1.5.2 (time 00' 30''/ 00' 56'')

Sound signal: Sine wave
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 130 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 2000 -2500 ms)

Observations on sound dynamism: by decreasing the note durations, the speed (velocity) of movement increases. Using note duration of 130 ms, the 8-note groups still create a long and regular rhythmic pattern, which is too predictable and static. However, in terms of dynamism, they function better compared to note durations of 250 ms.

With short and almost regular absolute distances, dynamism is not as satisfactory as using longer and irregular absolute distances.

Test 1.5.3 (time 01' 00''/ 01' 36'')

Sound signal: Sine wave
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 130 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 1000 -4000 ms)

Observations on sound dynamism: with longer and variable absolute distances, sound dynamism produced by relative position variations improves substantially. Due to the fact that the perception of the front-rear sound locations is severely limited and only one unique left-right dialog is perceived, relative position variations tend to be monotonous and not sufficiently dynamic.

Test 1.5.4 (time 01' 40 ''/ 01' 58 '')

Sound signal: Sine wave
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 60 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 400 -2400 ms)

Observations on sound dynamism: with this note duration, the first and last notes of the 8-note group become more important to differentiate the successive relative positions from one another. The last note is perceived as a reflection or echo of the first one.

Although the overall sound is very similar, relative position variations cause each 8-note group to be perceived as distinct, especially with long absolute distances.

Left-right positions of the first and last notes are more recognizable than the rest. The notes in between are no longer recognizable, and they are perceived as reflections or extensions of the first note.

Relative position variations are enough to provide dynamism, especially when the absolute distance is perceived as regular.

Test 1.5.5 (time 02' 02 '' / 02' 28 '')

Sound signal: Sine wave
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz
Amplitude: CONSTANT (-15 dB)
Note duration: 60 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 800 -4000 ms)

Observations on sound dynamism: dynamism is increased when the absolute distance reaches 4000 ms. The unexpected entrances for each successive 8-note group confer more dynamism. However, with this note duration, the rhythmic pattern of each 8-note group is too regular.

Sound attribute variations are well perceived.

Left-right sound sources are the only ones that are well localized.

Test 1.5.6 (time 02' 31'' / 02' 44'')

Sound signal: Sine wave
Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz
Volume: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 30 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (\pm 700-2000 ms)

Observations on sound dynamism: sound trajectories are well-perceived, although their overall sound quality is very similar. However, relative position variations distinguish them, especially using long absolute distances.

Dynamism is improved with variable absolute distances. The unexpected entrances for each successive 8-note group confer a high degree of dynamism.

Left-right sound sources are the only ones that are well-localized.

Besides the predominance of the first and last notes and the left-right positions, the other notes do have an influence on the overall perception of the 8-note group, as they are perceived as extensions or reflections of the first note (shadows).

Test 1.5.7 (time 02' 45''/ 02' 52'')

SOUND: Sine wave
Phase of the sine wave for each repetition: IDENTICAL
Frequency: 408 Hz
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 15 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (\pm 300-1000 ms)

Observations on sound dynamism: the 8-note groups are perceived as one unique auditory event (the sound duration of the entire 8-note group is now 119 ms long). The left-right spatial dialog is now perceived as one attack on one side with a very short echo on the other.

The following list shows the relation between the spatial localization of the two auditory events with the first and last notes:

-Relative distance	1357-2468 is perceived at left with a very weak echo right middle.
''	4213-6875 is perceived at right with a strong echo left-middle.
''	8756-4312 is perceived at right-rear with an echo left-middle.

- ” 5841-2376 is perceived at left with an echo rear-middle.
- ” 2413-6857 is perceived at right-rear both as first auditory event and echo.
- ” 7865-1243 is perceived at left-rear and the echo at left-rear.
- ” 3618-2754 is perceived at left and the echo at left.
- ” 6428-7513 is perceived at right-rear and the echo at left-middle.

The overall sound duration is very short, and the perception of sound variations is almost unidentifiable.

The situation is quite dynamic, as the combination of attacks and reflections (echoes) has a different spatial and slightly different sound quality for every group.

Sound locations 7 and 8 are here well-perceived, which increases the dynamism of sound trajectories.

Test 1.5.8 (time 02' 55 ''/ 03' 12'')

Sound signal: Sine wave

Phase of the sine wave for each repetition: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Sound sources: 8 CHANNEL

Note duration: 15 ms

Relative distance: 0 ms

Absolute distance: VARIABLE (± 2000 ms).

Observations on sound dynamism: with this note duration, long absolute distances impede the perception of sound quality and sound position variations between the successive 8-note groups.

CONCLUSIONS:

- 1) As already seen in the previous tests, using relative position variations with the same frequency, amplitude, and note duration create the perception of important pitch, loudness, and tone color variations. However, variations in texture and rhythm are not perceived.
- 2) By decreasing the note duration, the successive positions of the notes in the 8-note groups change more rapidly, increasing the speed (velocity) of movement. The 8-

note groups using note durations of 130, 60, 30, and 15 ms are perceived as one sound impulse more than the sum of eight independent notes. Thus, the perception of sound attribute variations as well as sound localization are more blurred. However, the overall sound is more attractive and dynamic compared to longer note durations, so they could be used in a real musical situation.

- 3) Although the overall sound quality of the successive 8-note groups with different relative positions is very similar, relative position variations distinguish them, especially when the absolute distance is well-balanced with the note duration.
- 4) With short and almost regular absolute distances, dynamism is less satisfactory. Thus, the absolute distance must be irregular. In general, short note durations require shorter relative distances compared to long note durations.
- 5) Besides the predominance of the first and last notes of the 8-note groups and the left-right positions, the other notes do have an influence on the overall perception of the group, as they are perceived as reflections and echoes of the first note, influencing as well the perception of pitch, loudness, and tone color.

Test 1.6: 8-note Groups with Relative and Absolute Position Variations.

Objective: to determine to what extent simultaneous relative and absolute position variations confer more dynamism compared to the previous test, where only relative position variations are applied.

The 12 absolute position rows are the following:

1.	Track 1-8	1234-5678	7.	Track 49-56	1123-4567
2.	Track 9-16	6666-8888	8.	Track 57-64	2244-6687
3.	Track 17-24	4444-7777	9.	Track 65-72	3333-5555
4.	Track 25-32	1133-6688	10.	Track 73-80	4446-6677
5.	Track 33-40	2244-5577	11.	Track 81-88	1111-2222
6.	Track 41-48	1113-3355	12.	Track 89-96	3344-5678

(The maximal sound-space density 8/1 is not used in this test).

Test 1.6.1 (time 00' 01''/ 00' 26'')

Sound signal: SINE WAVE
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 250 ms
Relative distance: 0 ms
Absolute distance: 1-2 sec.

Observations on sound dynamism: although sound localization and the perception of sound attribute variations are different for each 8-note group, absolute position variations are not enough to create a dynamic situation. As with using relative position variations only, the rhythms of the 8-note groups are perceived as too regular and predictable, which creates a static musical situation.

Pitch, loudness, and tone color variations, while prominent, are not enough to confer interest and dynamism to the successive 8-note groups. In addition, relative position variations are especially static when using sound-space density 8/2.

Test 1.6.2 (time 00' 30''/ 00' 56'')

Sound signal: SINE WAVE
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 130 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 300 -1500 ms)

Observations on sound dynamism: decreasing the note durations to 130 ms, the 8-note groups are more dynamic than in the previous test, but still too regular and predictable. Pitch, loudness, and tone color variations are not sufficient to confer interest and dynamism to the successive 8-note groups.

Generally, absolute position variations are not dynamic enough, especially in those cases where the notes in the 8-note groups are repeated more than three times in the same sound source, which occurs when using sound-space density 8/2 (i.e. 4444 / 5555).

Test 1.6.3 (time 01' 00''/ 01' 36'')

Sound signal: Sine wave
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 130 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 1000 -4000 ms)

Observations on sound dynamism: using longer and variable absolute distances, dynamism is substantially improved, although the perception of a melodic contour (similar to microtonal variations) of notes in the 8-note group is too static and monotonous. Thus, with this note duration and variable absolute distances, sound-space density variations are not sufficient to create a dynamic musical situation.

Test 1.6.3 (time 01' 40 ''/ 01' 58'')

Sound signal: Sine wave
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 60 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 400 -2400 ms)

Observations on sound dynamism: this note duration functions very well with all the absolute positions, including sound-space density 8/2. Different absolute position and sound-space densities create rhythm and texture variations, which confer enough dynamism to the successive 8-note group.

The first and last notes of the 8-note groups become more important concerning sound localization.

With this note duration, only left-right sound sources seem to be recognizable, as front-rear sound sources are not perceived. The notes in the 8-note groups after the first note are perceived as extensions or reflections of the first note, and provide the 8-note groups with a particular sound quality and 8-note group duration.

Test 1.6.4 (time 02' 02 ''/ 02' 28'')

Sound signal: Sine wave
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 60 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 800 -4000 ms)

Observations on sound dynamism: dynamism is increased when the distance between the 8-note groups is irregular. The unexpected entrances for the successive 8-note groups confer more dynamism to the successive repetitions.

By decreasing the note durations, sound attribute variations are less perceptible, and the perception of sound location and texture variations between the groups becomes more important.

Test 1.6.5 (time 02' 31 ''/ 02' 44'')

Sound signal: Sine wave
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 30 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 700 -2000 ms)

Observations on sound dynamism: the perception of rhythm and texture and sound localization variations is greatly improved compared to the previous tests.

The use of variable absolute distances contributes substantially to achieve dynamism, due to the unexpected entrances of the successive 8-note groups.

With this note duration, only the first and last notes are perceived, together with right-left sound locations. As in the previous tests, the notes after the first notes are perceived as reflections or extensions of the first note, and provide the 8-note groups a particular sound quality, rhythm, and group duration.

Test 1.6.6 (time 02' 46''/ 02' 58'')

Sound signal: Sine wave
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 30 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 700 -2000 ms)

Observations on sound dynamism: using 8-note groups with variable relative and absolute positions proves to be more dynamic than the same relative position through different absolute positions, because more rhythm and texture variations are perceived.

Test 1.6.7 (time 03' 00''/ 03' 07'')

Sound signal: Sine wave
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 15 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 300 -1000 ms)

Observations on sound dynamism: with this note duration, sound attribute and texture variations are more homogeneous. The only well-perceived change is the movement of sound from right to the left or vice versa, depending on the relative and absolute positions.

The perception of texture variations is very homogeneous.

Test 1.6.8 (time 03' 11 ''/ 03' 27'')

Sound signal: Sine wave
Frequency: 408 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 15 ms
Relative distance: 0 ms
Absolute distance: VARIABLE (± 2000 ms).

Not much difference compared to test 1.6.8.

CONCLUSIONS:

- 1) When two contrasting absolute positions and sound locations occur, they create textures with an internal rhythm. Thus, the perception of rhythm and texture variations occurs together with absolute position variations, in addition to sound attribute variations. The same absolute position can present rhythm and texture variations as soon as the relative positions are different.
- 2) The absolute position variations create important rhythm and texture variations, especially using note durations of 130, 60, and 30 ms. However, they are not sufficient to create a dynamic musical situation, especially when long silences between the 8-note groups are used.

Experiment 2: tests on sound perception and sound localization when successive 8-note groups are played through different relative positions.

Test 2.1: Sustained Tones.

Objective: to determine to what extent relative position variations confer dynamism to sustained tones, which implies the use of successive 8-note groups with the same sound signal, frequency, note duration, and relative and absolute distances of 0 ms, through relative position variations and the same absolute position 1234-5678 (sound-space density 8/8).

Test 2.1.1 (time 00' 01"/ 00' 42")

Sound signal: SINE WAVE

Fade in/Fade out: YES (10 ms)

Frequency: 53 Hz

Phase of the sine wave for each repetition: IDENTICAL

Amplitude: CONSTANT (0 dB)

Sound sources: 8 CHANNEL

Note duration: 386 ms

Number of cycles: 20
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: pitch, loudness, and tone color variations are well-perceived, and they are always accompanied by important sound pressure level variations, supporting the claim in chapter 2 that sound pressure variations are the most important variations for the perception of loudness and tone color variations. Despite using 10 ms fade-in and fade-out envelopes, a very low transient sound is perceived at the beginning of each tone.

Observations on sound localization: although sound localization is quite blurred, it is possible to perceive tones coming from all four aural hemispheres, even from the rear. In this respect, the transient sound aids the perception of sound locations and creates at the same time different sound trajectories.

Test 2.1.2 (time 00' 50''/ 01' 30'')

Sound signal: SINE WAVE
Fade in/Fade out: NO
Frequency: 53 Hz
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (0 dB)
Sound sources: 8 CHANNEL
Note duration: 386 ms
Number of cycles: 20
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: without fade in and fade out envelopes, transient sound predominates, and pitch and tone color variations are not as well-perceived as in the previous test. Transient sounds are perceived almost identically, except for differences in loudness. As soon as sound attribute variations become less important, the listener focuses on sound localization.

Observations on sound localization: sound locations and sound trajectories are better perceived in the previous test.

Test 2.1.3 (time 02' 00"/ 02' 18")

Sound signal: SINE WAVE
Frequency: 159 Hz
Fade in/Fade out: YES (10 ms)
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 180 ms
Number of cycles: 29
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: pitch, loudness, and tone color variations are very well-perceived. Although the amplitude is the same for all the notes inside the 8-note groups, some of them are perceived much louder than the others, creating an internal rhythm.

Observations on sound localization: this note duration implies faster movement of the notes in the 8-note groups, and sound localization diminishes the front-rear sound sources, locating all sounds at the sides.

Test 2.1.4 (time 02' 25"/ 02' 46")

Sound signal: SINE WAVE
Frequency: 159 Hz
Fade in/Fade out: NO
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 180 ms
Number of cycles: 29
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: same as test 2.1.2.

Observations on sound localization: with this note duration front-rear sound localization is improved, although the perception of sound coming from the sides still

predominates.

Test 2.1.5 (time 03' 00"/ 03' 22")

Sound signal: SINE WAVE
Frequency: 212 Hz
Fade in/Fade out: YES (10 ms)
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 92 ms
Number of cycles: 20
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: with this note duration, the perception of pitch, loudness, and tone color variations seem to be more uniform. Only differences in loudness are evident.

Observations on sound localization: sound localization is more blurred compared to the previous tests. All sounds are perceived as coming from the sides, while front and rear sound sources are completely diminished.

Test 2.1.6 (time 03' 25"/ 03' 45")

Sound signal: SINE WAVE
Frequency: 212 Hz
Fade in/Fade out: NO
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 92 ms
Number of cycles: 20
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: same as the previous test.

Observations on sound localization: the transient sounds perceived at the beginning and end of each note aid sound localization. However, sound localization at the sides still

predominates, while front and rear sound sources are completely diminished.

Test 2.1.7 (time 03' 50''/ 04' 08'')

Sound signal: SINE WAVE
Frequency: 318 Hz
Fade in/Fade out: YES (10 ms)
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 46 ms
Number of cycles: 14
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: with this frequency and note duration, the individual notes in the 8-note groups are no longer perceived. Instead, only a diffuse sound field is perceived.

Observations on sound localization: the same occurs with sound localization, as diffuse sound fields imply that no individual sound locations are perceived.

Test 2.1.8 (time 04' 10''/ 04' 28'')

Sound signal: SINE WAVE
Frequency: 318 Hz
Fade in/Fade out: NO
Phase of the sine wave for each repetition: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Sound sources: 8 CHANNEL
Note duration: 46 ms
Number of cycles: 14
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: Original (O) relative position rows
Absolute positions: 8/8

Observations on sound perception: with this frequency and note duration, the transient sounds of each individual note in the 8-note groups create a granular texture that is superimposed on the pitched notes, which as in the previous test create a diffuse sound field.

Observations on sound localization: the transient sounds are perceived as sound points, which are localized almost exclusively in the left-right aural hemispheres.

Test 2.1.9 (time 04' 35"/ 06' 10")

Sound signal: SINE WAVE

Frequency: 408 Hz

Fade in/Fade out: YES (10 ms)

Phase of the sine wave for each repetition: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Sound sources: 8 CHANNEL

Note duration: 1 ms sound dilation from 1 ms to 226 ms

Relative distance: 1 ms distance decrease from 226 ms to 0 ms

Absolute distance: 0 ms

Relative positions: Original (O) relative position rows

Absolute positions: 8/8

Observations on sound perception: with shorter note durations the pitch is higher and becomes gradually lower as soon as the note duration increases. Around 40 ms the pitch is totally defined, which in this case is 12 Hz. From approximately 1 to 33 ms tones are a mixture of pitched and non-pitch. As the note duration increases, more pitch than non-pitch is perceived, and loudness and tone color variations are more evident. Variations in loudness predominate.

Observations on sound localization: sound localization is better perceived with shorter note durations. As soon as the pitched sound is more important compared to the non-pitched sound, sound localization is more blurred. Increasing note duration tends to create a diffuse sound field, although in this case each individual note in the 8-note group is still perceptible.

Test 2.1.10 (time 06' 30"/ 09' 15")

Sound signal: SQUARE WAVE

Frequency: 272 Hz

Phase of the sine wave for each repetition: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Sound sources: 8 CHANNEL

Note duration: 56 ms

Number of cycles: 14

Relative distance: 0 ms

Absolute distance: 0 ms

Relative positions: Original (O) relative position rows

Absolute positions: 8/8

Observations on sound perception: this frequency and note duration create a diffuse sound field, where the notes in the 8-note groups are barely differentiated from one another. Thus no pitch, loudness, or tone color variations are perceived. Using triangle waves, three tones are clearly perceived, the fundamental together with the third and fifth harmonics.

Observations on sound localization: no individual sound localizations for the notes in the 8-note groups, only a diffuse sound field.

Test 2.1.11 (time 09' 30''/ 11' 05'')

Sound signal: SINE WAVE

Frequency: 1224 Hz

Fade in/Fade out: YES (10 ms)

Phase of the sine wave for each repetition: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Sound sources: 8 CHANNEL

Note duration: 55 ms

Number of cycles: 54

Relative distance: 0 ms

Absolute distance: 0 ms

Relative positions: Original (O) relative position rows

Absolute positions: 8/8

Observations on sound perception: this frequency and note duration create a diffuse sound field, where the notes in the 8-note groups are not differentiated from one another. Thus no pitch, loudness, or tone color variations are perceived. With this frequency, although the sound signal is a triangle wave, only the fundamental tone is perceived.

Observations on sound localization: no individual sound localization for the notes in the 8-note groups is perceived, only a diffuse sound field.

CONCLUSIONS:

- 1) Pitch, loudness, and tone color variations are well-perceived, and they are always accompanied by important sound pressure level variations, supporting the claim in

chapter 1 that sound pressure variations are the most important variations for the perception of loudness and tone color variations.

- 2) Transient sound at the beginning of each note in the 8-note groups aids the perception of sound locations and creates at the same time different sound trajectories.
- 3) Transient sounds are perceived as almost identical to one another, except for differences in loudness. This supports the claim that sounds with complex upper structures problematize the perception of sound attribute variations produced by sound localization. As soon as sound attribute variations become less important, the listener focuses on sound localization. Although the amplitude is the same for all notes inside the 8-note groups, some of them are perceived as much louder than the others, creating an internal rhythm.
- 4) The 8-note groups with a frequency of 318 Hz and a note duration of 46 ms create diffuse sound fields, implying that neither the individual notes in the 8-note groups nor individual sound locations are perceived anymore.

Experiment 3: further tests on sound perception and sound localization using 5-note group attacks.

Test 3.1: 5-note Group Attacks.

Objective: to determine how the perception of sound location and sound attribute variations create a dynamic musical situation using 5-note groups with different frequencies and short note durations.

As we have already experienced in tests 1.5 and 1.6, the successive repetition of 8-note groups with the same frequency and note duration through different relative and absolute positions create variations in frequency, loudness, and tone color. Sound attribute variations are especially important when using long note durations beyond 125 ms, while they are almost indiscernible using shorter note durations. However, the problem with long note durations (250 to 125 ms) is that the 8-note groups create rhythmic patterns that are too regular and predictable. On the other hand, the 8-note groups are perceived as the sum of eight independent notes, creating melodic patterns (similar to microtonal intonation

variations), which are not sufficiently dynamic. Thus, the use of long note durations is here dismissed.

On the other hand, tests 1.5 and 1.6 show that relative and absolute position variations are not sufficiently dynamic when using 8-note groups with the same frequency, even with short note durations.

Therefore, this test uses 5-note groups with different frequencies and short note durations. The 5-note groups alternate five of the following seven frequencies: 159, 53, 212, 318, 477, 795, and 954 Hz. The following rows determine the relative frequency order for each 5-note group:

- | | |
|--------------------------------|--------------------------------|
| 1. 159 / 53 / 212 / 318 / 477 | 5. 477 / 795 / 954 / 159 / 53 |
| 2. 53 / 212 / 318 / 477 / 795 | 6. 795 / 954 / 159 / 318 / 212 |
| 3. 212 / 318 / 477 / 795 / 954 | 7. 954 / 159 / 53 / 212 / 318 |
| 4. 318 / 477 / 795 / 954 / 159 | 8. 159 / 795 / 212 / 318 / 477 |

To make each note group more dynamic, the test is repeated two times using different relative distances. First, the eight repetitions of the 5-note group are submitted to relative position variations only, while keeping the same absolute position (1234/ 5678, sound-space density 8/8). The second time, the same 5-note groups are submitted to simultaneous relative and absolute position variations. The relative and absolute position rows are as follows:

Relative position rows:

- | | |
|--------------|--------------|
| 1. 1357-2468 | 5. 2413-6857 |
| 2. 4213-6875 | 6. 7865-1243 |
| 3. 8756-4312 | 7. 3618-2754 |
| 4. 5841-2376 | 8. 6428-7513 |

Absolute position rows:

- | | | | | | |
|--------------|-----|---------------|--------------|-----|---------------|
| 1. 1234-5678 | 8/8 | (Track 1-8) | 7. 1123-4567 | 8/7 | (Track 49-56) |
| 2. 7777-7777 | 8/1 | (Track 9-16) | 8. 2446-6887 | 8/5 | (Track 57-64) |
| 3. 8888-6666 | 8/2 | (Track 17-24) | 9. 3333-5555 | 8/2 | (Track 65-72) |

4.	1133-5577	8/4	(Track 25-32)	10.	4446-6688	8/3	(Track 73-80)
5.	1111-3333	8/2	(Track 33-40)	11.	1111-2222	8/2	(Track 81-88)
6.	2244-6688	8/4	(Track 41-48)	12.	3344-5678	8/6	(Track 89-96)

Concerning note durations, each test uses 5-note groups with the same note duration. However, note durations vary from test to test, as indicated in the list of parameters at the beginning of each test.

At the same time, in order to make each 5-note group more dynamic, different relative distances will be used:

1 ms 5-note-groups				6 ms. 5-note-groups				11 ms. 5-note-groups			
1.	0	ms		1.	0, 0, 0, 0	ms		1.	11, 0, 3, 6	ms	
2.	1, 2, 3, 1	ms		2.	3, 6, 1, 3	ms		2.	23, 11, 6, 11	ms	
3.	6, 3, 1, 6	ms		3.	11, 6, 3, 11	ms		3.	0, 0, 0, 0	ms	
4.	11, 6, 3, 11	ms		4.	11, 6, 6, 23	ms		4.	3, 11, 23, 23	ms	
5.	11, 6, 23, 3	ms		5.	3, 6, 3, 11	ms		5.	6, 0, 3, 23	ms	
6.	23, 11, 11, 46	ms		6.	11, 11, 23, 11	ms		6.	23, 23, 11, 11	ms	
7.	11, 6, 23, 46	ms		7.	6, 23, 3, 11	ms		7.	23, 46, 11, 46	ms	
8.	46, 11, 23, 46	ms		8.	11, 23, 46, 11	ms		8.	11, 6, 23, 3	ms	

23 ms. 5-note-groups				46 ms. 5-note-groups			
1.	23, 0, 0, 23	ms		1.	23, 0, 46, 11	ms	
2.	23, 11, 23, 46	ms		2.	46, 0, 46, 46	ms	
3.	0, 0, 0, 0	ms		3.	46, 0, 0, 92	ms	
4.	0, 11, 23, 6	ms		4.	46, 92, 0, 0	ms	
5.	0, 23, 23, 46	ms		5.	0, 0, 46, 92	ms	
6.	23, 23, 0, 23	ms		6.	0, 0, 0, 0	ms	
7.	46, 0, 11, 23	ms		7.	23, 6, 11, 6	ms	
8.	0, 0, 46, 11	ms		8.	0, 23, 11, 92	ms	

Tests 3.1.1 (time: 00' 01" / 00' 10")

Same absolute position, variable relative positions.

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)

Amplitude: CONSTANT (-4,2 dB)

Sound sources: 8 CHANNELS

Note duration: 1 ms.

Relative distance: 1ms 8 relative distance row

Absolute distance: 1104 ms.

Relative position: 8 (O) relative position rows

Absolute position: SAME (1234/ 5678)

Observations on sound perception: variations in the perception of tone color and loudness are completely masked because of the use of different frequencies for each note in the 5-note groups. Only sound location variations are clearly perceived, although they have no influence on the perception of sound attribute variations. Even with the shortest note duration (1 ms), where only a transient sound is perceived, variations in the sound attributes are due to frequency variations. Sound texture variations are produced by variations in the relative distance.

Observations on sound localization: sound localization is different for each 5-note group. The first frequency of the 5-note group determines the sound location for the entire 5-note group, while the other frequencies are perceived as reflections and echoes of the primary auditory event, and it is difficult to determine their exact sound location.

Test 3.1.2 (time: 00' 15" / 00' 30")

Same as 1.6.1 with variable absolute positions.

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)

Amplitude: CONSTANT (-4,2 dB)

Sound sources: 8 CHANNELS

Note duration: 1 ms.

Relative distance: 1ms 8 relative distance row

Absolute distance: 1104 ms

Relative position: 8 (O) relative position rows

Absolute position: 12 absolute position rows

Observations on sound perception: not much difference compared to test 3.1.2. Again, frequency variations are so important that they mask the perception of sound attribute variations produced by sound localization.

Observations on sound localization: frequency variations are more important than sound localization variations, as absolute positions 9, 10, 11, and 12 repeat the same 5-note groups as 1, 2, 3, and 4; furthermore they are perceived as almost identical, even though

the absolute positions are different.

Test 3.1.3 (time: 00' 35" / 00' 45")

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)

Amplitude: CONSTANT (-4,2 dB)

Sound sources: 8 CHANNELS

Note duration: 6 ms.

Relative distance: 6 ms 8 relative distance rows

Absolute distance: 1104 ms.

Relative position: 8 (O) relative position rows

Absolute position: SAME (1234/ 5678)

Observations on sound perception: same as test 3.1.1. Frequency variations are so present that they mask the perception of the sound attribute variations produced by sound localization.

Observations on sound localization: sound localization is different for each 5-note group. The first frequency of the 5-note group determines sound location for the whole 5-note group. As soon as the listener assimilates the frequencies used for the successive 5-note groups (all the 5-note groups are based on the same seven frequencies), he or she starts to focus more on sound location.

Test 3.1.4 (time: 00' 50" / 01' 05")

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)

Amplitude: CONSTANT (-4,2 dB)

Sound sources: 8 CHANNELS

Note duration: 6 ms.

Relative distance: 1ms 8 relative distance row

Absolute distance: 1104 ms.

Relative position: 8 (O) relative position rows

Absolute position: 12 absolute position rows

Observations on sound perception: same as test 3.1.1.

Observations on sound localization: absolute position variations provide more dynamism than relative position variations alone.

Test 3.1.5 (time: 01' 10" / 01' 20")

Sound: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)

Amplitude: CONSTANT (-4,2 dB)

Sound sources: 8 CHANNELS

Note duration: 11 ms.

Relative distance: 11 ms 8 relative distance row

Absolute distance: 1104 ms

Relative position: 8 (O) relative position rows

Absolute position: SAME (1234/ 5678)

Observations on sound perception: same as tests 3.1.5. The only difference is that the frequencies involved in the 5-note group are better perceived and have more influence on the overall sound perception, especially with large relative distances.

Observations on sound localization: same as tests 3.1.5. The only difference is that sound localization is clearer.

Test 3.1.6 (time: 01' 26" / 01' 45")

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)

Amplitude: CONSTANT (-4,2 dB)

Sound sources: 8 CHANNELS

Note duration: 11 ms.

Relative distance: 11 ms 8 relative distance row.

Relative position: 8 (O) relative position rows

Absolute position: 12 absolute position rows

Absolute distance: 1104 ms.

Observations on sound perception: same as test 3.1.5.

Observations on sound localization: as soon as the sound localization of the five frequencies inside the 5-note groups is more differentiated, sound movement becomes more dynamic, as more sound-space density relations are perceived. Using longer note durations, the position of each frequency in the 5-note group is more differentiated, and absolute position variations are more dynamic than relative position variations.

Test 3.1.7 (time: 01' 50" / 02' 00")

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)
Amplitude: CONSTANT (-4,2 dB)
Sound sources: 8 CHANNELS
Note duration: 23 ms.
Relative distance: 23 ms 8 relative distance rows
Absolute distance: 1104 ms
Relative position: 8 (O) relative position rows
Absolute position: SAME (1234/ 5678)

Observations on sound perception: same as test 3.1.6.

Observations on sound localization: as soon as the perception of each frequency becomes more audible and more active with the increase of the note duration, sound localization becomes less important, and the attention focuses on frequency variations.

Test 3.1.8 (time: 02' 07" / 02' 21")

Sound signal: SINE WAVE
Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)
Amplitude: CONSTANT (-4,2 dB)
Sound sources: 8 CHANNELS
Note duration: 23 ms.
Relative distance: 23 ms 8 relative distance row.
Relative position: 8 (O) relative position rows
Absolute position: 12 absolute position rows
Absolute distance: 1104 ms.

Observations on sound perception: same as test 3.1.6.

Observations on sound localization: same as test 3.1.6.

Test 3.1.9 (time: 02' 26" / 02' 35")

Sound signal: SINE WAVE
Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)
Amplitude: CONSTANT (-4,2 dB)
Sound sources: 8 CHANNELS
Note duration: 46 ms.
Relative distance: 46 ms 8 relative distance row.
Relative position: 8 (O) relative position rows
Absolute position: SAME (1234/ 5678)
Absolute distance: 1104 ms.

Observations on sound perception: same as test 3.1.6.

Observations on sound localization: same as test 3.1.6.

Test 3.1.10 (time: 02' 39" / 02' 54")

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795, 954 Hz (following the 8 frequency rows)

Amplitude: CONSTANT (-4,2 dB)

Sound sources: 8 CHANNELS

Note duration: 46 ms

Relative distance: 46 ms 8 relative distance row

Relative position: 8 relative position rows

Absolute position: 12 absolute position rows

Absolute distance: 1104 ms

Observations on sound perception: same as test 3.1.6.

Observations on sound localization: same as test 3.1.6.

CONCLUSIONS:

- 1) As soon as the 5-note groups incorporate several frequencies, variations in the perception of tone color and loudness are completely masked . Only sound location variations are clearly perceived, although they have no influence on the perception of sound attribute variations. Even with the shortest note duration (1 ms), where only a transient sound is perceived, variations in the sound attributes are due to frequency variations. Sound texture variations are perceived, due to variations in the relative distance.
- 2) The perception of texture variations is due to variations in the relative distance.
- 3) Sound localization is more dynamic using absolute position variations, as they involve more sound-space density variations (from 8/1 to 8/5). Using relative position variations implies that only sound-space density 8/5 is used.
- 4) Using longer note durations, the position of each frequency in the 5-note groups is more differentiated, and absolute position variations create more dynamic musical situations than relative position variations alone.
- 5) As no big frequency differences occur between the 5-note groups, the listener rapidly assimilates the frequency variations, and sound localization becomes more important in the search for dynamism and variety. In this sense, the attention

focuses primary on those parameters that are more important in terms of sound dynamism, and follow a certain hierarchical order concerning their capacity to supply dynamism. The most important are frequency variations, followed by rhythm, amplitude, timbre, the perception of pitch, tone color, loudness involved in sound localization, and finally, sound localization.

- 6) As soon as frequency variations become more audible and active, sound localization becomes less important, and the attention focuses on the melodic patterns created by frequency variations.

Test 3.2: 5-note Groups Left-Right Space Dilation Rows.

Objective: the previous test 3.1 shows that the use of 5-note group with different frequencies masks the perception of the sound attribute variations produced by sound localization, which are an important goal in this research. This test is a further attempt to use space to create the perception of sound attribute variations of the same 5-note groups through the use of contrasting sound-space densities and sound trajectories.

The previous Test 3.1 shows that as soon as the listener assimilates the seven frequencies used in the 5-note groups, the dynamic situation created by frequency variations become too monotonous and predictable. At this moment, sound localization becomes more important, and the listener starts to perceive the variations created by relative and absolute position variations. In this sense, more dynamism is achieved by repeating some 5-note group through some (or all) absolute positions with little or no absolute distance between them. In these cases, the rapid change of sound locations through sound-space density variations creates the so-called “gestures”.

The initial situation is density 8/1 (sound source 7). All 5-note groups use absolute position 7777-7777, sound-space density 8/1 and sound source 7 as the initial absolute position and sound location when only one 5-note group is played. When a 5-note group is repeated several times (one after the other with little or no absolute distance), it moves through some or all of the absolute positions following the “left-right space dilation absolute positions rows” specified below, which imply the linear dilation of the 5-note group from sound source 7 through the left or right sound sources (see figure 16, p. 67).

At the same time, each relative position implies a different sound-space density relation.

Left-right space dilation absolute positions rows:

1.	1234-5678	8/8	Track 1-8)	7.	7788-6644	8/4	Track 49-56
2.	7777-7777	8/1	Track 9-16	8.	7755-3311	8/4	Track 57-64
3.	7864-2211	8/6	Track 17-24	9.	7866-4422	8/5	Track 65-72
4.	7755-5333	8/4	Track 25-32	10.	7533-1122	8/5	Track 73-80
5.	7788-8666	8/3	Track 33-40	11.	7777-8888	8/2	Track 81-88
6.	7531-1244	8/6	Track 41-48	12.	7777-5555	8/2	Track 89-96

In addition, in order to create a more dynamic musical situation, amplitude changes are also be applied to each absolute position, following the values specified below:

1.	Track 1-8	0 dB	7.	Track 49-56	-6 dB
2.	Track 9-16	0 dB	8.	Track 57-64	0 dB
3.	Track 17-24	-3 dB	9.	Track 65-72	-3 dB
4.	Track 25-32	-9 dB	10.	Track 73-80	+6 dB
5.	Track 33-40	-6 dB	11.	Track 81-88	0 dB
6.	Track 41-48	+3 dB	12.	Track 89-96	-3 dB

In order to compare the influences of sound localization and relative and absolute positions on the perception of 5-note groups, the following tests present every 5-note group two times, one immediately after the other with contrasting sound-space density relations: the first time with sound-space density 8/1 (sound source 7), and the second time following the left-right space dilation absolute position rows. Sometimes, after the 5-note groups are radiated by sound source 7 (sound-space density 8/1), they are repeated in another sound source (1, 2, 3, 4, 5, 6, or 8), thus changing its sound location.

Test 3.2.1 (time 00' 01" / 03' 05")

Sound signal: SINE WAVE

Frequency: 159, 53, 212, 318, 477, 795 and 954 Hz (following the previous 8 frequency in test 3.1)

Amplitude: Amplitude variations row

Sound sources: 8 CHANNELS

Note duration: 1, 6, 11, 23 and 46 ms

Relative distance: relative distance row (same as test 3.1)

Absolute distance: VARIABLE

Relative position: 8 relative position rows (same as test 3.1)

Absolute position: left-right space dilations absolute position row.

CONCLUSIONS:

- 1) As we see in test 3.1, the use of 5-note groups with different frequencies masks the perception of the sound attribute variations produced by sound localization. Comparing two simultaneous versions of the same 5-note group proves that the perception of sound attribute variations is masked by the presence of frequency variations. Although sound quality variations do occur, they are no longer important. In this sense, repeating a single 5-note group with sound-space density 8/1 in another sound source, or using the left-right sound dilation absolute position rows, creates some sound attribute variations. Anyway, these mild sound attribute variations are perceived because the exact same sound is repeated. As soon as the sound object is present in other variations, the perception of sound attribute variations is masked again.
- 2) The left-right sound dilation absolute positions rows have an important influence on the specific overall perception of the 5-note groups, as some frequencies are more audible and differentiated compared to sound density 8/1. We can assert that the frequencies inside the 5-note-groups are more differentiated by spreading them on the horizontal plane, thus increasing the distance between them.

Experiment 4: further tests on sound perception and sound localization using successive 8-note groups with relative and absolute position variations.

Test 4.1: Textures.

Objective: to experiment and evaluate to what extent relative and absolute position variations can create the perception of dynamic textures, i.e. dynamic contrasts in sound localization as well as the perception of sound attribute and texture variations.

Test 1.6 shows that successive 8-note groups with short note durations (60 and 30

ms) create textures, especially when played one after the other with little or no absolute distance. It proves as well that relative and absolute position variations modify the perception of such textures, as they produce the perception of sound attributes, i.e. pitch, loudness, tone color, rhythm, and sound-space density variations.

Experiment 4 attempts to explore such variations in greater detail. Test 4.1.1 explores to what extent playing successive 8-note groups through the (O), (I), (R), and (RI) relative position variations (see below) creates the perception of dynamic textures.

Relative position rows

	Original (O)	Retrograde (R)	Inversion (I)	Retrograde of the Inversion (RI)
1-	1357-2468	3157-8246	8642-7531	6842-1753
2-	4213-6875	4572-8163	5786-3124	5427-1836
3-	8756-4312	3421-5687	1243-5687	6578-4312
4-	5841-2376	7586-3142	4158-7623	2413-6857
5-	2413-6857	6732-1485	7586-3142	3267-8514
6-	7865-1243	2134-6578	2134-8756	7865-3421
7-	3618-2754	5786-3124	6381-7245	4213-6875
8-	6428-7513	8642-7531	3571-2486	1357-2468

Test 4.1.2 investigates to what extent the sum of relative and absolute position variations are able to create dynamic textures. The previous four relative position rows are played through the 12 absolute position rows specified below.

12 absolute position rows:

1-	1234-5678	8/8	(Track 1-8)	7-	1123-4567	8/7	(Track 49-56)
2-	6666-8888	8/2	(Track 9-16)	8-	2244-6687	8/5	(Track 57-64)
3-	4444-7777	8/2	(Track 17-24)	9-	3333-5555	8/2	(Track 65-72)
4-	1133-6688	8/3	(Track 25-32)	10-	4446-6677	8/3	(Track 73-80)
5-	2244-5577	8/4	(Track 33-40)	11-	1111-2222	8/2	(Track 81-88)
6-	1113-3355	8/3	(Track 41-48)	12-	3344-5678	8/6	(Track 89-96)

Test 4.1.1 (time 00' 01" / 00' 10")

Sound signal: SINE WAVE

Phase: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 13 ms

Relative distance: 0 ms

Absolute distance: ± 60 -100 ms

Relative position rows: (O), (I), (R), and (RI)

Absolute position rows: SAME (1234–5678)

Distance between the O, R relative position rows: VARIABLE (± 1 -2.4 sec.)

Observations: the (O), (I), (R), and (RI) relative-position rows are perceived as almost identical. Sound localization and sound attribute variations, although they are almost imperceptible, prevent the perception of the 8-note groups as identical. Therefore, relative position variations alone are not enough to create dynamic textures.

Test 4.1.2 (time 00' 11" / 02' 00")

Sound signal: SINE WAVE

Phase: IDENTICAL

Frequency: 408 Hz

Amplitude: CONSTANT (-15 dB)

Note duration: 13 ms

Relative distance: 0 ms

Absolute distance: ± 60 —100 ms

Relative positions: (O), (I), (R), and (RI)

Absolute positions: absolute position rows 1 to 11

Distance between the (O), (I), (R), and (RI) relative position rows: VARIABLE
(± 1 -2.4 sec.)

Observations: absolute position changes confer enough sound attribute, rhythm, and texture variation to the successive 8-note groups to create a dynamic musical situation.

CONCLUSIONS:

- 1) The (O), (I), (R), and (RI) relative position rows are perceived as almost identical. Sound position and sound attribute variations, while very mild, prevent the perception that the exact same 8-note groups are being repeated. Thus, relative

position variations alone are too subtle to be used in real musical situations.

- 2) Simultaneous relative and absolute position variations provide enough dynamism to the 8-note groups to create a satisfying dynamic musical situation, especially when the number of repeated 8-note groups varies with each absolute position. Although the musical situation is based on the same material, the textures created by the successive 8-note groups are perceived in perpetual change, involving the perception of sound attribute, rhythm, and texture variations.
- 3) Relative and absolute distances provide the successive 8-note groups a particular sound quality and texture.

Test 4.2: Continuums.

Objective: to evaluate to what extent relative and absolute position variations are able to create long homogeneous textures, using successive 8-note groups with the same sound signal, frequency, note duration, and relative and absolute distances. These long and homogeneous textures are defined by the term “continuum”.

In order to create long homogeneous textures (continuums), once the 8-note-groups have gone through all the (O), (I), (R), and (RI) relative position rows as well as the 12 absolute position rows, the resulting overall texture is repeated through its inversion, retrograde, and retrograde of the inversion. In doing so, it is possible to prevent the perception of repeated rhythmic patterns and pulses that occur when the relative and absolute position rows are looped following the same chronological order.

Test 4.2.1 (time 00' 01''/ 00' 35'')

Sound signal: Sine wave

Frequency: 53 Hz

Phase of the notes: IDENTICAL

Amplitude: CONSTANT (-11.2 dB)

Note duration: 10 ms

Relative distance: VARIABLE ($0 \geq 52$ ms)

Absolute distance: VARIABLE (± 23 ms)

Relative position: (O), (I), (R), and (RI)

Absolute positions: 12 absolute position rows

12 absolute positions row variations: (O), (I), (R), and (RI)

Distance between the successive absolute position rows: VARIABLE ($0 \geq 52$ ms)

Observations: simultaneous relative and absolute positions variations create a stable, uniform and dynamic texture (continuum) in perpetual change or motion, i.e. the same texture is perceived with sound attribute, rhythm, and texture variations.

Test 4.2.2 (Time 00' 40''/ 01' 40'')

Sound signal: Sine wave

Frequency: 212 Hz

Phase: IDENTICAL

Volume: CONSTANT (-11.2 dB)

Note duration: 23 ms

Relative distance: 23 ms

Absolute distance: VARIABLE ($0 \geq 34$ ms)

Relative positions: (O), (I), (R), and (RI)

Absolute positions: 12 absolute position rows

12 absolute positions row variations: (O), (I), (R), and (RI)

Distance between the successive absolute position rows: VARIABLE ($0 \geq 34$ ms)

Observations: using 8-note groups with these parameters creates a rough texture with a mixture of pitched and non-pitched sound. Similar to the previous tests, the successive relative and absolute position variations create a regular, stable, and uniform continuums in permanent change.

Test 4.2.3 (time 01' 45''/ 02' 31'')

Sound signal: Sine wave

Frequency: 318 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-11.2 dB)

Note duration: 46 ms

Relative distance: 16 ms

Absolute distance: 16 ms

Relative positions: (O), (I), (R), and (RI)

Absolute positions: 12 absolute position rows

12 absolute positions row variations: (O), (I), (R), and (RI)

Distance between the successive absolute positions: 16 ms

Observations: the 8-note groups with this parameters, create a texture with a smooth roughness, as the notes in the 8-note groups is perceived as independent sound points. Again, the successive relative and absolute position variations create a regular, stable, and

uniform continuum in permanent change.

Test 4.2.4 (time 02' 35''/ 03' 49'')

Sound signal: Sine wave

Frequency: 477 Hz

Phase: IDENTICAL

Volume: CONSTANT (-11.2 dB)

Note duration: 21 ms

Relative distance: 27 ms

Absolute distance: 27 ms

Relative positions: (O), (I), (R), and (RI)

Absolute positions: 12 absolute position rows

12 absolute positions row variations: (O), (I), (R), and (RI)

Distance between the successive absolute positions: 27 ms

Observations: same as the previous test.

Test 4.2.5 (time 03' 51''/ 04' 18'')

Sound signal: Sine wave

Frequency: 795 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-11.2 dB)

Note duration: 8 ms

Relative distance: 2 ms

Absolute distance: 2 ms

Relative positions: (O), (I), (R), and (RI)

Absolute positions: 12 absolute position rows

12 absolute positions row variations: (O), (I), (R), and (RI)

Distance between the successive absolute positions: 2 ms

Observations: the successive 8-note groups with this frequency, note duration, amplitude and relative and absolute distances, create a rough texture, and the sound quality is a mixture of pitched and non-pitched. Successive relative and absolute position variations create a regular, stable, and uniform sound continuum in permanent change.

CONCLUSIONS

- 1) The O, I, R, RI repetition of the entire (O), (I), (R), and (RI) relative position rows and 12 absolute position rows creates long homogeneous textures in permanent

motion called continuums, where the perception of repeated patterns and rhythmic pulses is avoided.

- 2) As frequency, note duration, amplitude, and relative and absolute distances remain the same throughout the continuum, they have a regular, stable, and uniform character. However, it is possible to create continuums in constant change by moving them through different sound-space densities and absolute positions.

Test 4.3: Static Textures (53, 159, 212, 318, 477, 795, 954 Hz)

Objective: to realize further experiments using 8-note-groups with one frequency, note duration, and invariable relative and absolute distances.

This test continues the previous test 4.2 and creates several textures using 8-note groups with one frequency (53, 159, 212, 318, 477, 795, or 945 Hz), one note duration (14, 37, 63, or 130 ms) and one relative and absolute distance (0, 4, 12, 21, 46, 67, 92, or 184 ms). Each of the 8-note groups moves partially or entirely through the same (O), (I), (R), and (RI) as in test 4.2, and the following 12 absolute position rows:

1-	1234-5678	8/8	(Track 1-8)	7-	6668-8777	8/3	(Track 49-56)
2-	1111-3333	8/2	(Track 9-16)	8-	1133-5577	8/4	(Track 57-64)
3-	2244-6688	8/4	(Track 17-24)	9-	2222-4444	8/2	(Track 65-72)
4-	5578-8644	8/5	(Track 25-32)	10-	4421-1355	8/5	(Track 73-80)
5-	6666-8888	8/2	(Track 33-40)	11-	5555-7777	8/2	(Track 81-88)
6-	1133-3222	8/3	(Track 41-48)	12-	3344-5678	8/6	(Track 89-96)

Unlike test 4.2, the 8-note groups with the same frequency and note duration present two differentiated sound qualities, one smooth (using fade-in and fade-out envelopes), and one rough (without fade-in and fade-out envelopes). In some cases both sound qualities are used during the same texture.

Test 4.3.1

(Time: 00' 01''/ 01' 17'' 1 sound source (sound-space density 8/1)
 01' 20''/ 02' 35'' 8 sound sources (8/8)
 01' 20''/ 02' 35'' 8 sound sources (8/8))

Sound signal: SINE WAVE
Frequency: 159 Hz
Phase: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Note duration: 1 ms
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: (O), (I), (R), and (RI) relative position rows
Absolute positions: 12 absolute position rows

Observations: relative distance the 8-note groups go through the successive 12 absolute position rows very quickly, and instead of a texture, a short gesture is perceived. Sound attribute, rhythm, and texture variations are perceived, although they change so fast that it is difficult to distinguish them. However, absolute position variations confer enough dynamism, so these short gestures could be used in a real musical situation.

Test 4.3.2 (time 00' 23"/ 01' 16")

Sound signal: SINE WAVE
Frequency: 159 Hz
Phase: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Note duration: 1 ms
Relative distance: 6 ms
Absolute distance: 6 ms
Relative positions: (O), (I), (R), and (RI) relative positions rows
Absolute positions: 12 absolute position rows

Observations: relative and absolute position variations provide enough dynamism to the successive 8-note groups, and create a dynamic musical situation. Depending on sound-space density, textures are smoother or rougher. Smooth textures are related to sound-space densities $8/3$ to $8/8$, while rough textures are related to sound-space densities $8/1$ and $8/2$. 8-note groups with no fade-in or fade-out envelopes accentuate the rough quality of sound.

Test 4.3.3 (time 01' 17"/ 01' 33")

Sound signal: SINE WAVE
Frequency: 159 Hz
Phase: IDENTICAL
Volume: CONSTANT (-15 dB)
Note duration: 1 ms

Relative distance: 23 ms
Absolute distance: 23 ms
Relative positions: (O), (I), (R), and (RI) relative positions rows
Absolute positions: 12 absolute position rows

Observations: same as previous Test 4.3.2. Sound attribute, rhythm, and texture variations are clearly perceived.

Test 4.3.4 (time 01' 35''/ 02' 30'')

Sound signal: SINE WAVE
Frequency: 159 Hz
Phase: IDENTICAL
Volume: CONSTANT (-15 dB)
Note durations: 1 ms
Relative distance: 92 ms
Absolute distance: 92 ms
Relative positions: (O), (I), (R), and (RI) relative positions rows
Absolute positions: 12 absolute position rows

Observations: with this note duration and relative distance, texture is perceived as the sum of isolated sound points. Through successive relative and absolute position variations, each sound point is perceived with a specific sound quality and specific location. Sometimes sound points create identifiable sound trajectories.

Test 4.3.5 (time 02' 34''/ 03' 00'')

Sound signal: SINE WAVE
Frequency: 53 Hz
Phase: IDENTICAL
Amplitude: CONSTANT (-15 dB)
Note duration: 10 ms
Relative distance: 12 ms
Absolute distance: 12 ms
Relative positions: (O), (I), (R), and (RI) relative positions rows
Absolute positions: 12 absolute position rows

Observations: with this low frequency, it is difficult to perceive texture variations, and the combination of notes with and without fade-in and fade-out envelopes is more efficient to create texture and sound quality variations.

However, sound-space density variations are very important to create a spatial

rhythm, which is the consequence of the time intervals of permanence and change of the 8-note groups through different successive absolute positions.

Test 4.3.6 (time 03' 00 ''/ 03' 23'')

Sound signal: SINE WAVE

Frequency: 53 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 10 ms

Relative distance: 21 ms

Absolute distance: 21 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: texture variations are similar to test 4.3.4. Regarding the perception of sound quality variations, important variations in the perception of pitch and tone color occur between successive absolute positions.

Even in the case where absolute position variations do not create significant texture variations, sound-space density variations are very important, as they move the 8-note groups through different sound locations, creating the spatial rhythms mentioned in test 4.3.4.

Test 4.3.7 (time 03' 26 ''/ 03' 58'')

Sound signal: SINE WAVE

Frequency: 53 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 10 ms

Relative distance: 43 ms

Absolute distance: 43 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: concerning sound texture, same observations as test 4.3.4. Important pitch and tone color variations are perceived between successive absolute positions. As texture and sound quality variations are quite similar through successive absolute positions, the sound localization, spatial rhythm, and texture variations become more important.

Test 4.3.8 (time 04' 00 ''/ 04' 43'')

Sound signal: SINE WAVE

Frequency: 53 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 10 ms

Relative distance: 93 ms

Absolute distance: 93 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: with this note duration and relative distance, the texture is perceived as the sum of isolated sound points, as in test 4.3.3. Through successive relative and absolute positions, sound points are perceived with specific sound qualities, especially pitch and sound location. Sound localization and texture variations as well as spatial rhythm become very important to create dynamism.

Test 4.3.9 (time 04' 48 ''/ 04' 43'')

Sound signal: SINE WAVE

Frequency: 53 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 10 ms

Relative distance: 184 ms

Absolute distance: 184 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: with this relative distance, sound localization, texture variations, and spatial rhythm become even more important than in the previous tests, creating a high degree of dynamism. Pitch, loudness, and tone color variations are more prominent as well.

Test 4.3.10 (time 05' 26''/ 06' 28'')

Sound signal: SINE WAVE

Frequency: 212 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 23 ms

Relative distance: 23 ms

Absolute distance: 23 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: important texture variations are perceived, especially when combining notes with and without fade-in and fade-out envelopes. Sound attribute variations are perceived as well, although pitch variations are maybe the most present, especially with fade-in and fade-out envelopes. Notes without fades create a more homogeneous texture, and the perception of texture variations is clearer.

Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.11 (time 06' 30''/ 07' 05'')

Sound signal: SINE WAVE

Frequency: 212 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 23 ms

Relative distance: 46 ms

Absolute distance: 46 ms

Relative positions: relative positions row

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: same as test 4.3.8.

Sound movement and spatial rhythm create a high degree of dynamism. Sometimes relative and absolute positions create trajectories in the space, which aids the perception of sound attribute and texture variations.

Test 4.3.12 (time 07' 06''/ 07' 39'')

Sound signal: SINE WAVE

Frequency: 212 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 23 ms

Relative distance: 92 ms

Absolute distance: 92 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: with this relative distance, dynamism is achieved by the alternation of notes with and without fade-in and fade-out envelopes more than through relative and absolute position variations. Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.13 (time 07' 40''/ 07' 53'')

Sound signal: SINE WAVE

Frequency: 212 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 23 ms

Relative distance: 67 ms

Absolute distance: 67 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: with this note duration and relative distance, the texture is perceived as the sum of isolated sound points. Through successive relative and absolute positions, sound points are perceived with specific sound qualities, especially pitch variations. Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.14 (time 08' 00''/ 08' 24'')

Sound signal: SINE WAVE

Frequency: 318 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 46 ms

Relative distance: 0 ms

Absolute distance: 0 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: with this frequency, note duration and relative distance, sound attribute and texture variations are very important, especially pitch variations. Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.15 (time 08' 28''/ 08' 45'')

Sound signal: SINE WAVE

Frequency: 318 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-15 dB)

Note duration: 46 ms

Relative distance: 29 ms

Absolute distance: 29 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: this relative distance creates relevant sound attribute and texture variations, especially pitch variations. Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.16 (time 08' 50''/ 09' 30'')

Sound signal: SINE WAVE

Frequency: 477 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-22 dB)

Note duration: 23 ms

Relative distance: 0 ms

Absolute distance: 0 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: relative and absolute position variations are not dynamic enough to create a dynamic texture. Only sound attribute variations are clearly perceived, especially pitch variations. Spatial rhythm is almost nonexistent, as the resulting texture is perceived as too homogeneous.

Test 4.3.17 (time 09' 32''/ 11' 04'')

Sound signal: SINE WAVE

Frequency: 477 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-22 dB)

Note duration: 23 ms

Relative distance: 26 ms

Absolute distance: 26 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: as with test 4.3.14, relative and absolute position variations do not create a dynamic texture. Only sound attribute variations are clearly perceived, especially variations in pitch. This is especially true when the listener remains immobile in the center of the eight speakers. When the listener moves toward and away from the loudspeakers, different textures do emerge, thus creating a much more dynamic musical situation.

Spatial rhythm is almost nonexistent, as the resulting texture is perceived as too homogeneous.

Test 4.3.18 (time 11' 09 ''/ 12' 46'')

Sound signal: SINE WAVE

Frequency: 477 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-22 dB)

Note duration: 23 ms

Relative distance: VARIABLE (23-46-92 ms)

Absolute distance: VARIABLE (23-46-92 ms)

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: the combination of three different relative distances improves the perception of texture variations, while relative and absolute position variations play a secondary role. Sound attribute variations are clearly perceived, especially variations in pitch.

Spatial rhythm is almost nonexistent as the 8-note groups move through the successive absolute positions too fast. In order to achieve spatial rhythm, the 8-note groups must remain more time in each absolute position.

Test 4.3.19 (time 12' 50''/ 13' 39'')

Sound signal: SINE WAVE

Frequency: 795 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-22 dB)

Note duration: 10 ms

Relative distance: VARIABLE (0-8-13-23-46-92 ms)

Absolute distance: VARIABLE (0-8-13-23-46-92 ms)

Relative positions: (O), (I), (R), and (RI) relative positions rows
Absolute positions: 12 absolute position rows

Observations: as with test 4.3.16, the combination of six different relative distances improves the perception of texture variations, although not as a consequence of relative and absolute position variations. Sound quality variations are clearly perceived, especially pitch variations.

Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.20 (time 13' 39"/ 14' 00")

Sound signal: SINE WAVE
Frequency: 795 Hz
Phase: IDENTICAL
Amplitude: CONSTANT (-22 dB)
Note duration: 10 ms
Relative distance: 0 ms
Absolute distance: 0 ms
Relative positions: (O), (I), (R), and (RI) relative positions rows
Absolute positions: 12 absolute position rows

Observations: this note duration and relative distance create a very smooth texture.
Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.21 (time 14' 02"/ 14' 54")

Sound signal: SINE WAVE
Frequency: 795 Hz
Phase: IDENTICAL
Amplitude: CONSTANT (-22 dB)
Note duration: 10 ms
Relative distance: VARIABLE (0-8-13-23-46-92 ms)
Absolute distance: VARIABLE (0-8-13-23-46-92 ms)
Relative positions: (O), (I), (R), and (RI) relative positions rows
Absolute positions: 12 absolute position rows

Observations: same as tests 4.3.16 and 4.3.17. The movement of the listener around the room toward and away from the loudspeakers creates a much more dynamic musical situation, in terms of both sound attribute and texture variations. Moving around the room functions especially well with homogeneous textures.

Test 4.3.22 (time 14' 57"/ 15' 16")

Sound signal: SINE WAVE

Frequency: 945 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-22 dB)

Note duration: 6 ms

Relative distance: VARIABLE (0-8-13-23-46-92 ms)

Absolute distance: VARIABLE (0-8-13-23-46-92 ms)

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: the combination of three different relative distances improves the perception of texture variations, while relative and absolute position variations play a secondary role. Sound attribute variations are clearly perceived, especially pitch variations.

Sound movement and spatial rhythm create a high degree of dynamism.

Test 4.3.23 (time 15' 24 " / 15' 47")

Sound signal: SINE WAVE

Frequency: 945 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-22 dB)

Note duration: 6 ms

Relative distance: VARIABLE (23-48 ms)

Absolute distance: 0 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: same as test 4.3.20.

Test 4.3.24 (time 15' 24 " / 15' 47")

Sound signal: SINE WAVE

Frequency: 945 Hz

Phase: IDENTICAL

Amplitude: CONSTANT (-22 dB)

Note duration: 6 ms

Relative distance: 92 ms

Absolute distance: 0 ms

Relative positions: (O), (I), (R), and (RI) relative positions rows

Absolute positions: 12 absolute position rows

Observations: same as test 4.3.20.

CONCLUSIONS:

- 1) With note durations of 1 ms and no relative and absolute distances, the successive 8-note groups create short gestures, which are dynamic enough to be used in a real musical situation. Depending on sound-space density, textures are smoother or rougher. Smooth textures are related to sound-space densities $8/3$ to $8/8$, while rough textures are related to sound-space densities $8/1$ and $8/2$. 8-note groups with no fade-in or fade-out envelopes accentuate the rough quality of sound.
- 2) Depending on the note duration and relative distance, as for instance with note durations 1 ms and relative and absolute distance 92 ms, texture may be perceived as the sum of isolated sound points. Through successive relative and absolute position variations, each sound point is perceived with a specific sound quality quality and specific location. Sometimes sound points create identifiable sound trajectories.
- 4) Sound-space density variations are very important to create a spatial rhythm, which is the consequence of the change of the 8-note groups through different successive absolute positions. Sound movement and spatial rhythm create a high degree of dynamism.
- 5) With frequency 477 Hz, note duration 23 ms and relative and absolute distance 0 ms, relative and absolute position variations are not enough to create a dynamic texture, and the perception of spatial rhythm is nonexistent as the texture is too homogeneous. Only sound attribute variations are clearly perceived, especially pitch variations. Spatial rhythm is almost nonexistent, as the resulting texture is perceived as too homogeneous. This is especially true when the listener remains immobile in the center of the eight speakers. However, it is observed that when the listener moves toward and away from the loudspeakers, different textures do emerge, thus creating a much more dynamic musical situation.

- 6) The combination of three different relative distances improves the perception of texture variations, while relative and absolute position variations play a secondary role.

Test 4.4: Polyphonic Textures.

Objective: to determine to what extent the dialog between sound movement and sound-space density variations, and the perception of sound attribute, rhythm, and texture variations is still perceptible or masked by the complexity of the polyphonic structure.

The textures used in the polyphonic texture are the ones created in test 4.3. Therefore, each polyphonic texture is formed by several textures, which, unlike continuums, are not played continuously from beginning to end but go through some absolute positions only. Figures 64, 65, 90, 91, and 92 show the spatial trajectories of each individual texture through different absolute positions.

Each polyphonic texture is presented two times: the first time it is presented using sound-space density 8/1 only (no spatialization), while in the second each individual texture involved in the polyphonic texture goes through different sound-space densities. The intention is to experience how the space differentiates the textures involved in a polyphonic situation, in order to supply sound clarity and transparency.

It is important to mention that each texture in test 4.3 is already subject to relative and absolute position variations. The polyphonic textures reorganizes each texture again through new absolute position variations. The absolute positions are different for each polyphonic texture, and are specified in the left margin of figures 61, 62, 63, (pp. 142, 143, and 144) and figures 90, 91, and 92 (pp. 218, 219, and 220 in appendix II) as well as at the initial list of parameters for each test. The polyphonic textures respect the principle of no overlapping.

Test 4.4.1 (time: 00' 01" / 00' 32" and 00' 35" / 01' 06") (see figure 61, p. 142)

Sound signal: SINE WAVE (with and without fade-in/ fade-out envelopes)

Frequency: 53 Hz

Number of textures involved: 5 textures

Amplitude inside each 8-note-group: VARIABLE

Amplitude for each absolute position: VARIABLE

Note duration: 10 ms (same for all 5 textures using 53 Hz)

Relative distances for each texture: variable (± 1 — 23 ms), 23, 46, 92 and 184 ms
 Absolute distances for each texture: variable (± 1 — 23 ms), 23, 46, 92 and 184 ms
 Relative positions: (O), (I), (R), and (RI) relative position rows
 Absolute positions: 12 absolute position rows

1-	7777-7777	8/1	(Track 1-8)	7-	6666-8888	8/2	(Track 49-56)
2-	2244-6688	8/4	(Track 9-16)	8-	1133-5577	8/4	(Track 57-64)
3-	2222-4444	8/2	(Track 17-24)	9-	4444-4444	8/1	(Track 65-72)
4-	2222-2222	8/1	(Track 25-32)	10-	2226-6688	8/3	(Track 73-80)
5-	3333-5555	8/2	(Track 33-40)	11-	6666-6666	8/1	(Track 81-88)
6-	3333-3333	8/1	(Track 41-48)	12-	1111-1111	8/1	(Track 89-96)

Test 4.4.2 (time: 01' 10" / 01' 55" and 02' 00" / 02' 42") (see figure 62, p. 143)

Sound signals: SINE WAVE and TRIANGLE WAVE (with and without fade-in and fade-out envelopes)

Frequency: 159 Hz

Number of textures involved: 5 textures

Amplitude inside each 8-note group: VARIABLE

Amplitude for each absolute position: VARIABLE

Note duration: 1 ms

Relative distance for each texture: 0, 6, 23, 92 ms and linear dilate from 47 to 69 ms

Absolute distance for each texture: 0, 6, 23, 92 ms and linear dilate. from 47 to 69 ms

Relative positions: (O), (I), (R), and (RI) relative position rows

Absolute positions: 12 absolute position rows

1-	6666-6666	8/1	(Track 1-8)	7-	7777-5555	8/2	(Track 49-56)
2-	1133-5577	8/4	(Track 9-16)	8-	2244-6688	8/4	(Track 57-64)
3-	1111-3333	8/2	(Track 17-24)	9-	3333-3333	8/1	(Track 65-72)
4-	1111-1111	8/1	(Track 25-32)	10-	1115-5577	8/3	(Track 73-80)
5-	2222-4444	8/2	(Track 33-40)	11-	5555-5555	8/1	(Track 81-88)
6-	2222-2222	8/1	(Track 41-48)	12-	8888-8888	8/1	(Track 89-96)

Test 4.4.3 (time: 02' 46" / 03' 12" and 03' 14" / 03' 41") (see figure 63, p. 144)

Sound signals: SINE WAVE and TRIANGLE WAVE (with and without fade-in/fade-out envelopes)

Frequency: 318 Hz

Number of textures involved: 6 textures

Amplitude inside each 8-note group: VARIABLE

Amplitude for each absolute position: VARIABLE

Note duration: 46 ms

Relative distance for each texture: 0, 11, 23, 46, 92, and 184 ms
 Absolute distance for each texture: 0, 11, 23, 46, 92, and 184 ms
 Relative positions: (O), (I), (R), and (RI) relative position rows
 Absolute positions: 12 absolute position rows

1-	1111-1111	8/1	(Track 1-8)	7-	2222-4444	8/2	(Track 49-56)
2-	5577-8866	8/4	(Track 9-16)	8-	3311-2244	8/4	(Track 57-64)
3-	8888-6666	8/2	(Track 17-24)	9-	6666-6666	8/1	(Track 65-72)
4-	8888-8888	8/1	(Track 25-32)	10-	3331-1122	8/3	(Track 73-80)
5-	4444-6666	8/2	(Track 33-40)	11-	4444-4444	8/1	(Track 81-88)
6-	5555-5555	8/1	(Track 41-48)	12-	7777-7777	8/1	(Track 89-96)

Test 4.4.4 (time: 03' 44" / 04' 11" and 04' 14" / 04' 40") (see figure 90, p. 218)

Sound signals: SINE WAVE and TRIANGLE WAVE (with and without fade-in and fade-out envelopes)

Frequency: 477 Hz

Number of textures involved: 5 textures

Amplitude inside each 8-note group: VARIABLE

Amplitude for each absolute position: VARIABLE

Note duration: 23 ms

Relative distance for each texture: 0, 11, 23, 46 and 92 ms

Absolute distance for each texture: 0, 11, 23, 46 and 92 ms

Relative positions: relative position row

Relative position variations: (O), (I), (R), and (RI) relative position rows

Absolute positions: absolute position row

1-	6666-6666	8/1	(Track 1-8)	7-	5577-8866	8/4	(Track 49-56)
2-	2244-6688	8/4	(Track 9-16)	8-	3311-2244	8/4	(Track 57-64)
3-	7777-5555	8/2	(Track 17-24)	9-	4444-4444	8/1	(Track 65-72)
4-	8888-8888	8/1	(Track 25-32)	10-	1115-5577	8/3	(Track 73-80)
5-	2222-4444	8/2	(Track 33-40)	11-	2222-2222	8/1	(Track 81-88)
6-	3333-3333	8/1	(Track 41-48)	12-	7777-7777	8/1	(Track 89-96)

Test 4.4.5 (time: 04' 42" / 05' 01" and 05' 04" / 05' 22") (see figure 91, p. 219)

Sound signals: SINE WAVE and TRIANGLE WAVE (with and without fade-in/fade-out envelopes)

Frequency: 795 Hz

Number of textures involved: 5 textures

Amplitude inside each 8-note group: VARIABLE

Amplitude for each absolute position: VARIABLE

Note duration: 10 ms

Relative distance for each texture: variable, 11, 23, 46 and 92 ms
 Absolute distance for each texture: variable, 11, 23, 46 and 92 ms
 Relative positions: (O), (I), (R), and (RI) relative position rows
 Absolute positions: absolute position row

1-	7777-7777	8/1	(Track 1-8)	7-	3333-5555	8/2	(Track 49-56)
2-	3331-1122	8/3	(Track 9-16)	8-	6666-4444	8/2	(Track 57-64)
3-	8888-6666	8/2	(Track 17-24)	9-	5555-5555	8/1	(Track 65-72)
4-	1111-2222	8/2	(Track 25-32)	10-	7778-8866	8/3	(Track 73-80)
5-	3333-1111	8/2	(Track 33-40)	11-	7777-8888	8/2	(Track 81-88)
6-	4444-4444	8/1	(Track 41-48)	12-	6666-6666	8/1	(Track 89-96)

Test 4.4.6 (time: 05' 26" / 05' 50" and 05' 53" / 06' 19 ") (see figure 92, p. 220)

Sound signals: SINE WAVE and TRIANGLE WAVE (with and without fade-in and fade-out envelopes)

Frequency: 954 Hz

Number of textures involved: 6 textures

Amplitude inside each 8-note group: VARIABLE

Amplitude for each absolute position: VARIABLE

Note duration: 6 ms

Relative distance for each texture: 0, 11, 23, 46, 92 and 184 ms

Absolute distance for each texture: 0, 11, 23, 46, 92 and 184 ms

Relative positions: (O), (I), (R), and (RI) relative position rows

Absolute positions: absolute position row

1-	1111-1111	8/1	(Track 1-8)	7-	2222-4444	8/2	(Track 49-56)
2-	5577-8866	8/4	(Track 9-16)	8-	3311-2244	8/4	(Track 57-64)
3-	8888-6666	8/2	(Track 17-24)	9-	6666-6666	8/1	(Track 65-72)
4-	8888-8888	8/1	(Track 25-32)	10-	3331-1122	8/3	(Track 73-80)
5-	4444-6666	8/2	(Track 33-40)	11-	4444-4444	8/1	(Track 81-88)
6-	5555-5555	8/1	(Track 41-48)	12-	7777-7777	8/1	(Track 89-96)

CONCLUSIONS:

- 1) The absolute position rows have an influence on the specific overall perception of the polyphonic textures, as some textures are more important and differentiated compared to sound density 8/1. Space confers sound clarity and transparency to polyphonic texture. Sound-space density relations also confer sound attribute, rhythm and texture variations to the 8-note groups, which are especially dynamic

using textures with 318, 477, and 795 Hz.

- 2) In general, with sound-space 8/1 the individual textures are indeed perceived, although as soon as the texture with the shorter note distance becomes louder than the others, the other simultaneous textures with longer distances are no longer perceived.
- 4) Using sound location and sound-space density relations implies that the individual textures in the polyphonic texture are better perceived. The division of space into different areas and the movement of the same texture from one sound source to another with sound-space density variations provides a high degree of dynamism to the polyphonic texture. However, even though a polyphonic texture is indeed perceived, it is difficult to isolate each texture from the others and perceive its spatial trajectories as well as its sound attribute, rhythm, and texture variations.
- 5) Many reasons may be the cause of such confusion. First, each layer appears, changes its absolute position three or four times relatively fast, and disappears. In consequence, too many variations occur simultaneously, in the number of the textures, sound-space densities, sound locations, and variations in the perception of the sound attribute, rhythm, and texture variations. Second, the textures involved in the polyphonic texture involved texture are quite similar, as they use the same frequency. What is perceived with is the mutation of one unique texture through different levels of roughness and smoothness, instead of a dynamic polyphonic texture. Third, texture and sound location variations occur very rapidly. The speed of the spatial changes and the short duration of each texture do not permit the listener to distinguish each texture from the others and perceive its position and spatial movement inside the textural polyphony.
- 6) As each texture is not clearly differentiated from the others, the listener cannot establish a direct relation between sound movement and texture variations. Without this dialog between space and sound perception, the textures are not useful for this research.
- 7) It is important to mention that clarity and transparency of polyphonic textures can be better achieved by increasing the distance between the sound sources, as the space permits better isolation of one texture from the others.

Test 4.5: Double Polyphonic Textures

Objective: the previous test 4.4 shows that instead of perceiving each texture individually, the polyphonic texture is perceived as the mutation of a single texture through different levels of roughness and smoothness. The main reason for this is that too many temporal and spatial variations are occurring simultaneously. Although clarity and transparency are achieved, the listener is not able to identify and isolate each individual texture and perceive its sound attribute, rhythm, and texture variations.

Test 3.5 tries to create an interesting musical situation by using several polyphonic textures simultaneously. Considering that the listener perceives the polyphonic textures as the variation of a single texture, it could be that using simultaneous polyphonic textures with different pitches could help isolate each texture and follow its evolution in time and space, thus creating a more interesting musical situation.

To this end two different double polyphonic textures are created, each one using four of the previous polyphonic textures: (1) 212, 318, 477, and 795 Hz, and (2) 53, 159, 795, and 954 Hz.

Each texture goes through processes of spatial dilation and contraction, from density 8/1 through 8/2 to 8/8 and the reverse. Consequently, each texture undergoes a slow and gradual expansion in space, which could help the perception of sound quality and sound texture variations, as well as the identification of each texture.

In order to differentiate each polyphonic texture in space as much as possible, at the beginning they are radiated by distant sound sources situated at opposite sides of the four aural hemispheres. This also implies that they are radiated using the highest sound-space density possible (8/1). The absolute positions for each texture are the following:

Polyphonic Texture 1:	1111-1111	(8/1) (Track 1-8)
	1111-3333	(8/2) (Track 9-16)
	1234-5678	(8/8) (Track 17-24)
Polyphonic Texture 2:	5555-5555	(8/1) (Track 25-32)
	5555-7777	(8/2) (Track 33-40)
	1234-5678	(8/8) (Track 41-48)

Polyphonic Texture 3: 8888-8888 (8/1) (Track 49-56)
 8888-6666 (8/2) (Track 57-64)
 1234-5678 (8/8), (Track 65-72)

Polyphonic Texture 4: 4444-4444 (8/1) (Track 73-80)
 2222-4444 (8/2) (Track 81-88)
 1234-5678 (8/8) (Track 89-96)

Test 4.5.1 (time: 00' 01''/ 00' 56'') (see figure 64, p. 146)

Sound signal: SINE WAVE (with and without fade-in / fade-out envelopes)
Number of textures involved: 4 textures
Frequencies for each texture: 212, 318, 477, and 795 Hz
Amplitude inside each 8-note group: 0 dB
Amplitude for each absolute position: 0 dB
Absolute positions and sound-space densities: sound-space density dilation and contraction absolute position row as specified above.

Test 4.5.2 (time: 00' 01''/ 01' 18'') (see figure 65, p. 147)

Sound signal: SINE WAVE and TRIANGLE WAVE (with and without fade-in and fade out envelopes)
Number of textures involved: 4 textures
Frequencies for each texture: 53, 159, 795, and 954 Hz
Volume inside each 8 note group: 0 dB
Volume for each absolute position: 0 dB
Absolute positions and sound space densities: sound-space density dilation and contraction absolute position row as specified above.

CONCLUSIONS:

In both cases it is very easy to identify and follow each polyphonic texture separately, even when all of them occupy the same sound-space density (8/8). However, each polyphonic texture is perceived as the mutation of the same layer (texture) through different levels of roughness and smoothness, and the fact that each polyphonic texture includes five different textures is not perceived at all in any of the three sound-space densities used. The proposed double polyphony is then perceived as a regular four-texture polyphony, and each layer involves one unique texture.

These double polyphonic textures are perceived as dynamic musical situations. However, if we compare them with the piece *Polyphonic Continuum*, we find them less successful. Why is that possible, if we consider that the textures involved in the polyphonic texture are more dynamic than the ones used in *Polyphonic Continuum*?

The main reason may be that both in the polyphonic texture and the double polyphonic texture, the sound attribute, rhythm, and texture variations are not related to sound location and sound-space density variations. In *Polyphonic Continuum*, sound perception is related to the movement of sounds in space. Any change in the sound-space density is followed by important changes in the perception of the sound attribute, rhythm, and texture variations, creating a dialog between sound perception and sound spatialization, which is favored by spatially differentiating each texture and simplifying the sound material to four invariable (static) textures.

With the polyphonic textures and double polyphonic textures presented here, the listening is limited to the contemplation of a musical situation where the cause-effect relations between sound and space are nonexistent, so everything occurs for no apparent reason.

Experiment 5: Sound Objects

Test 5.1: Sound Objects (159, 212, and 318 Hz)

Objectives: test 4.3 shows how relative and absolute position variations provide dynamism to static textures. Instead of long polyphonic textures, this test aims to investigate to what extent sound location and sound-space density variations influence the sound perception of short sound objects.

As with test 4.3, each sound object uses four textures with the same frequency but different relative and absolute distances. In addition, each texture presents two contrasting sound qualities, i.e. with or without fade-in and fade-out envelopes.

Each object is repeated eleven times following the eleven complementary absolute position rows (see below). In order to supply more dynamism to the successive sound objects, each texture undergoes sound duration and amplitude variations, which are different for each sound object. The amplitude varies from 0 to -21 dB.

In order to differentiate the textures involved in each sound object, they follow the law of no superposition. For this purpose, the space is divided into different areas with a particular sound-space density, resulting in the following 11 complementary absolute position rows:

For the 159 and 212 Hz sound objects:

1-	1111-1111	2-	1111-1111	3-	3333-3333	4-	1111-3333
	1111-1111		2222-2222		4444-4444		2222-4444
	1111-1111		7777-7777		5555-5555		5555-7777
	1111-1111		8888-8888		6666-6666		6666-8888
5-	3331-1222	6-	1111-3333	7-	3331-1222	8-	1133-5577
	4444-4444		2222-4444		4444-4444		2222-2222
	5555-7777		5555-5555		5555-5555		4444-4444
	6666-8888		7778-8666		7778-8666		6666-8888
9-	1111-3333	10-	1111-1111	11-	1234-5678		
	2244-6688		2222-2222		1234-5678		
	5555-5555		3333-3333		1234-5678		
	7777-7777		4468-8755		1234-5678		

For the 318 Hz Sound Objects:

1-	6666-6666	2-	1111-1111	3-	2222-2222	4-	1111-2222
	6666-6666		3333-3333		4444-4444		3333-5555
	6666-6666		6666-6666		5555-5555		4444-6666
	6666-6666		8888-8888		7777-7777		7777-8888
5-	1111-1111	6-	1111-2222	7-	1111-1111	8-	3311-2244
	2224-4666		3335-5777		2224-4666		5555-5555
	3333-5555		2222-4444		3335-5777		6666-6666
	7777-8888		8888-8888		8888-8888		7777-8888
9-	1111-2222	10-	5531-1244	11-	1234-5678		
	3333-3333		6666-6666		1234-5678		
	4444-4444		7777-7777		1234-5678		
	5577-8866		8888-8888		1234-5678		

Regarding the principle of no overlapping, an exception is made with sound-space density 8/1, where all four textures are played in one unique sound source, and sound-space density 8/8, where all textures are spread throughout the same 8 loudspeakers. These situations are accepted because it is necessary to determine how sound behaves with the highest and lowest sound-space situations possible. In order to provide dynamism, it could be necessary to use them to create sound attribute and texture contrasts.

After the objects are played through the 11 sound-space density rows, they are repeated in the retrograde, inversion, and inversion of the retrograde. In this way, while the sound material is the same, variations in the order of the textures inside each object, as well as the order of the objects themselves, create a different perception of the same sound material.

Test 5.1.1 (time 00'00" / 01'04") (see figure 71, p. 156)

Sound signal: SINE WAVE
 Sound Object: 4 texture sound object
 Frequency: 159Hz
 Amplitude: VARIABLE (± 0 / -21dB)
 Sound sources: 8 CHANNELS
 Note duration: 1 ms.
 Relative distances for each texture: 0, 6, 23, 92 ms
 Absolute distance for each texture: 0, 6, 23, 92 ms
 Absolute position: first 11 complementary absolute position rows

Test 5.1.2 (time 01'08" / 02'16") (see figure 72, p. 157)

Sound signal: SINE WAVE
 Sound Object: 4 texture sound object
 Frequency: 212 Hz
 Amplitude: VARIABLE (± 0 / -21dB)
 Sound sources: 8 CHANNELS
 Note duration: 23 ms.
 Relative distances for each texture: 0, 23, 46, 92 ms
 Absolute distance for each texture: 0, 23, 46, 92 ms
 Absolute position: first 11 complementary absolute position rows

Test 5.1.3 (time 02'18" / 03'26") (see figure 93, p. 221)

Sound signal: SINE WAVE
 Sound Object: 4 texture sound object
 Frequency: 318 Hz

Amplitude: VARIABLE (± 0 / -21dB)

Sound sources: 8 CHANNELS

Note duration: 46 ms.

Relative distances for each texture: 11, 23, 46, 92 ms

Absolute distance for each texture: 0, 23, 46, 92 ms

Absolute position: second 11 complementary absolute position rows

CONCLUSIONS:

In general, the perception of sound attribute, rhythm, and texture variations as consequences of sound location and sound-space density variations are not as well perceived as with continuums. The main reasons are that

- 1) the duration of the sound object is not long enough to permit perception of each texture,
- 2) relative distance variations and the use of sounds with and without fades mask the subtle variations produced by relative and absolute position variations, and
- 3) each texture inside each sound object is presented only in one absolute position. Thus, the immediate movement from two contiguous absolute positions and sound-space density relations does not occur, which makes it even more difficult to perceive the mild sound quality and sound texture variations between two sound objects, especially when there is some distance between them.

However, relative and absolute position variations help to provide dynamism to a musical situation where the same sound material is repeated several times, although the effects of such movement on sound attributes and texture are not perceived clearly enough.

Consequently, the arrangement of the sounds in different areas with different sound-space density relations, while not evident, do participate to a greater or lesser extent in providing sound variations to the same material.

On the other hand, the law of no superposition functions very well to provide sound clarity, as each part is well-differentiated from the others in space.

Test 5.2: Further Tests with Sound Objects.

Objective: to improve the perception of sound attribute, rhythm, and texture variations produced by relative and absolute position variations in test 5.1.

In test 5.2, each texture in the sound object is presented two to several times, one immediately after the other, through different absolute positions. Consequently, the duration of each texture is longer and better perceived in relation to the previous test.

Each sound object includes six different textures, although only a maximum of four occur at the same time.

In order to experiment with sounds with multiple partials, some textures include triangle waves or square waves as sound signals.

Tests 5.2.1, 5.2.2, 5.2.3, and 5.2.4 present each texture separately to experience and evaluate the perception of sound attribute and texture variations produced by relative and absolute position variations, while tests 5.2.5 present six sound objects created with the these sound materials.

Test 5.2.1 Sound Material 1-8

(time :	1.	00' 01 / 00' 13"	5.	00' 50" / 00' 56"
		Note Duration: 12 ms		Note Duration: 7 ms
	2.	00' 15" / 00' 29"	6.	00' 57" / 01' 02"
		Note Duration: 11 ms		Note Duration: 6 ms
	3.	00' 31" / 00' 39"	7.	01' 04" / 01' 08"
		Note Duration: 10 ms		Note Duration: 4 ms
	4.	00' 42" / 00' 49"	8.	01' 10" / 01' 15"
		Note Duration: 9 ms		Note Duration: 1-3 ms)

Sound signal: TRIANGLE WAVES (with filter equalization)

Number of textures: 9 independent textures

Frequency: 408 Hz

Amplitude: VARIABLE

Sound sources: 8 CHANNELS

Note durations: 1-3, 4, 5, 6, 7, 9, 10, 11, and 12 ms.

Relative distances: 0 ms.

Relative position:

-Note durations 1-3, 11, and 12 ms

1357-2468-6745-23

-Note durations 10, 9, 7, 6, 4 ms

5463-7281-8273-64

Absolute positions:

1-	1111-1111	8/1	(Track 1-8)	7-	1234-5678	8/8	(Track 49-56)
2-	2222-2222	8/1	(Track 9-16)	8-	1112-2444	8/3	(Track 57-64)
3-	6666-8888	8/2	(Track 17-24)	9-	5557-7888	8/3	(Track 65-72)
4-	1111-3333	8/2	(Track 25-32)	10-	3312-4688	8/6	(Track 73-80)
5-	5577-8866	8/4	(Track 33-40)	11-	2211-3577	8/5	(Track 81-88)
6-	3311-2244	8/4	(Track 41-48)	12-	7777-7777	8/1	(Track 89-96)

Test 5.2.2 Sound Material 10 (time: 01' 16" / 01' 48")

Sound signal: SINE WAVE

Sound quality: notes without fade-in and fade-out envelopes.

Frequency: 408 Hz

Amplitude: VARIABLE

Sound sources: 8 CHANNELS

Note durations: progressive dilation of the notes from 1 to 55 ms.

Relative distances: 0 ms.

Relative position: 8271-81
3254-7687

Absolute position: same as Test 4.2.1.

Test 5.2.3 Sound Material 11 (time: 01' 52" / 02' 08")

Sound signal: SQUARE WAVE (with filter equalization)

Number of textures: 1 texture

Frequency: 408 Hz

Amplitude: VARIABLE

Sound sources: 8 CHANNELS

Note durations: 55 ms.

Relative distances: 0 ms.

Relative position: 1357-2468
6745-231
8172-6354
5362-71
8765-4321
3254-768
5746-3524

Absolute position: same as Test 4.2.1

Test 5.2.4 Sound Material 12 (time: 02' 12" / 02' 26")

Sound signal: TRIANGLE WAVES (with filter equalization)

Number of textures: 1 texture

Frequency: 408 Hz
 Amplitude: VARIABLE
 Sound sources: 8 CHANNELS
 Note durations: 55 ms.
 Relative distances: 0 ms.
 Relative position: same as Test 4.2.3
 Absolute position: same as Test 4.2.1.

Observations: searching for the maximum contrast and dynamism in the sound attribute and texture variations, textures do not follow the chronological order dictated by the absolute position rows, but jump from one position to another. For instance, the final absolute positions for the sound material with note duration 12 ms is the following:

1-	1111-1111	8/1	(Track 1-8)
2 (3)-	6666-8888	8/2	(Track 17-24)
3 (5)-	5577-8866	8/4	(Track 33-40)
4 (7)-	1234-5678	8/8	(Track 49-56)
5 (8)-	1112-2444	8/3	(Track 57-64)
6 (10)-	3312-4688	8/6	(Track 73-80)
7 (12)-	7777-7777	8/1	(Track 89-96)
8 (11)-	2211-3577	8/5	(Track 81-88)
9 (4)-	1111-3333	8/2	(Track 25-32)

These sound trajectories prove that contrasting sound-space densities produce the perception of more sound attribute and texture variations.

Test 5.2.5 (Time 02' 58" / 03' 31") (see figures 75 and 76, pp. 161-162)

Sound Objects 1-6

In order to differentiate the parts of the sound object as much as possible, the spatial overlapping of the parts is not allowed, i.e. different parts cannot occupy the same area or sound source(s) at the same time. For this reason, the sound object is organized according to the following complementary absolute position rows (separated by groups of 3, 4, 5, or 6 absolute positions):

Sound objects 1, 2, and 3

1-	1111-1111	8/1	(Track 1)	12-	2222-2222	8/1	(Track 2)
2-	2222-4444	8/2	(Track 9-16)	13-	3333-1111	8/2	(Track 65-72)
3-	3357-7866	8/5	(Track 17-24)	14-	5557-7888	8/3	(Track 73-80)
				15-	6666-6666	8/1	(Track 6)
4-	7777-7777	8/1	(Track 7)	16-	4444-4444	8/1	(Track 4)
5-	5553-3111	8/3	(Track 25-32)				
6-	2224-4666	8/3	(Track 33-40)	17-	5555-5555	8/1	(Track 5)
7-	8888--8888	8/1	(Track 8)	18-	7788-6644	8/4	(Track 81-88)
				19-	3331-1222	8/3	(Track 89-96)
8-	3333-3333	8/1	(Track 3)				
9-	8888-6666	8/2	(Track 41-48)				
10-	1112-2244	8/3	(Track 49-56)				
11-	5555-7777	8/2	(Track 57-64)				

Sound objects 4, 5, and 6

1-	1111-1111	8/1	(Track 1)	12-	5555-5555	8/1	(Track 5)
2-	2222-4444	8/2	(Track 9-16)	13-	7788-6644	8/4	(Track 57-64)
3-	3357-7866	8/5	(Track 17-24)	14-	2222-2222	8/1	(Track 2)
				15-	1111-3333	8/2	(Track 65-72)
4-	7777-7777	8/1	(Track 7)				
5-	5533-1122	8/3	(Track 25-32)	16-	7778-8666	8/3	(Track 73-80)
6-	8886-6444	8/3	(Track 33-40)	17-	6666-8888	8/2	(Track 81-88)
				18-	4444-4444	8/1	(Track 4)
7-	3333-3333	8/1	(Track 3)	19-	1234-5678	8/8	(Track 89-96)
8-	5555-7777	8/2	(Track 41-48)				
9-	1112-2444	8/3	(Track 49-56)				
10-	8888-8888	8/1	(Track 8)				
11-	6666-6666	8/1	(Track 6)				

The division into groups indicates that all eight sound sources are used and none of

them is repeated. The textures can occupy all absolute positions and respect the principle of no overlapping.

In order to provide more dynamism to the successive repetitions, the sounds also undergo variations in the amplitude and sound duration.

Figures 75 and 76 (pp. 161-162) represent the temporal and spatial organization of each sound object, i.e. which textures are involved in each sound object, their temporal organization, their duration, and their movement through different sound-space densities.

Observations on the perception of sound attribute, rhythm, and texture variations: in general, sound attribute and texture variations produced by sound location and sound-space density variations are not as well-perceived as with the continuums. The main reason is that the sonic complexity of the sound objects due to the use of different frequencies prevents the listener from perceiving those variations produced by sound location and sound-space density variations. However, even when they are poorly perceived, they do exist, providing more variety and dynamism to the overall sound perception.

CONCLUSIONS:

In order to perceive sound attribute, rhythm, and texture variations produced by sound location and sound-space density variations, sounds have to be as static as possible and long enough that the subtle variations produced by absolute position variations are perceived. The best example is the continuums, which use textures with no frequency and relative and absolute distance variations. What functions very well with continuums, does not work with short objects, especially when other frequency variations are involved.

However, with short sound objects, even when it is not possible to perceive sound attribute, rhythm, and texture variations produced by sound location and sound-space density variations, they do exist, and provide more variety and dynamism to the overall sound situation.

Sound position variations also provide dynamism to a musical situation where the same sound material is repeated several times, especially when movement is associated with the perception of sound attribute, rhythm, and texture variations. The principle of no overlapping functions very well to provide clarity to sound movement, as each layer is more differentiated from the others.

APPENDIX III: DVDs 1 and 2 containing Pro Tools sessions with the audio corresponding to the experiments.

DVD 1:

DVD 2:

PART 2: COMPOSITIONS

Part 2 represents the practical part of the thesis, and includes DVD 3 with three acousmatic compositions:

- 1) *Topos*
- 2) *Polyphonic Continuum*
- 3) *Musical Situation 1*

DVD 3 contains a Pro Tools file with the octophonic version of each piece, and is prepared to be performed using eight loudspeakers arranged around the audience as shown in figure 19 (p.70).

Unfortunately, it is not possible to include the version of the pieces that use forty or forty-two channels, as the space of a DVD is not sufficient to store them.

IMPORTANT: The recorded amplitude level is 0 dB (attention to the output level at the beginning of each piece!!). The level must be adjusted depending to the size of each room. In this sense, *MUSICAL SITUATION 1* should start with a loudness of f to ff, and the resulting level must remain for the whole piece. Concerning *CONTINUUM*, loudness should reach ff to fff around 09'20'', or the maximum level that is not dangerous for the auditory system. This should be the reference. Consequently, loudness at the beginning of the piece should be p to pp.

The optimal performance conditions require the use of a darkened room, as dark as possible, so the vision of the real space has little or no influence on the sound space.

DVD 3: