A Synopsis of Sound - Image Transforms based on the Chromaticism of Music

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Abstract: *- Numerous algorithms have been proposed for image to sound and sound to image transforms. Based on heuristic assignments of sound frequencies to RGB values, they perform effective mappings between musical entities (notes) and values for optical wavelengths. In this paper, the chromaticism of the sound domain is taken into account and the coloring of the performed music is depicted for interrelated sound segments that have acoustic polymorphism and form entities of pitch organization. This algorithm helps visualize musical files according to their melodic structure and not only according to their temporal characteristics (i.e. rhythm).*

Key-Words: *- Sound to Image Transforms, Visualizations, Chromatic Index of Music.*

1 Introduction

Sounds are perceived as one dimensional signals whereas images are though as entities with more dimensions. Indeed, all the sounds that the human auditory channel may perceive are assorted within the 50 Hz – 20 kHz frequency range. Therefore, sound signals, and especially the musical ones, are characterized by a vector $\boldsymbol{v} = (f, \Delta t)$ depicting their frequency and their duration. In terms of music perception this seems to be a coarse approach, waiving the artistic dimension of music as a *performing* art; however, it has served as the basis for developing algorithms for sound to image and image to sound transforms.

On the other end, images are signals characterized by a frequency within the optical range, or, as it has been the tradition in Physics, with a wavelength λ. According to the International Commission on Illumination (CIE) any real colour can be expressed as a mixture of three CIE primaries **X**, **Y**, **Z** [22]. Therefore, a given colour C of wavelength λ can be expressed by (1):

$$C_\lambda = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z} \qquad (1)$$

where the coefficients *XYZ*, called *tristimulus values*, can be calculated using the CIE colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ (see Fig. 1):

$$X = k\int_\lambda \bar{x}(\lambda)\Phi(\lambda)\mathrm{d}\lambda \qquad Y = k\int_\lambda \bar{y}(\lambda)\Phi(\lambda)\mathrm{d}\lambda$$

$$Z = k\int_\lambda \bar{z}(\lambda)\Phi(\lambda)\mathrm{d}\lambda \qquad (2)$$

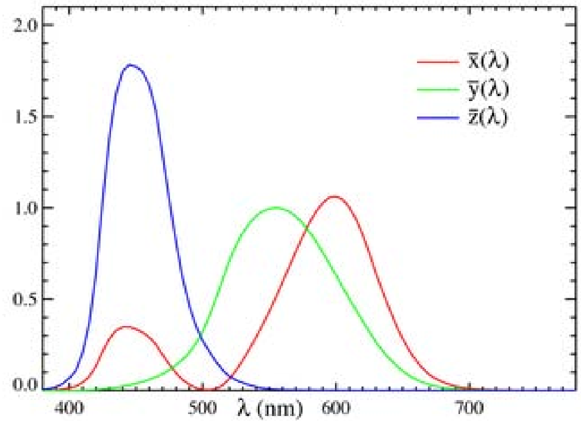


Fig. 1. The CIE 1931 colour matching functions. They serve as the starting point for quantitative analyses of coloured objects.

$\Phi(\lambda)$ is the spectral distribution of light stimulus, and k, a normalizing constant.

The normalization of the *X*, *Y*, and *Z* values results in the production of the *x*, *y*, and *z* values respectively:

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z} \qquad (3)$$

Since $x + y + z = 1$, z may be omitted. Therefore, one may use only the x and y values, known as the *chromaticity coordinates*, to plot the *CIE(x,y)* diagram in Fig. 2.

It is clear that this rationale, conceiving images as entities characterized by their wavelength λ and being represented by the *x*, *y*, and *z* analog predicates is characteristic of the pre-digital age nomenclature. It may be useful to an astronomer measuring signals coming from distant galaxies, or

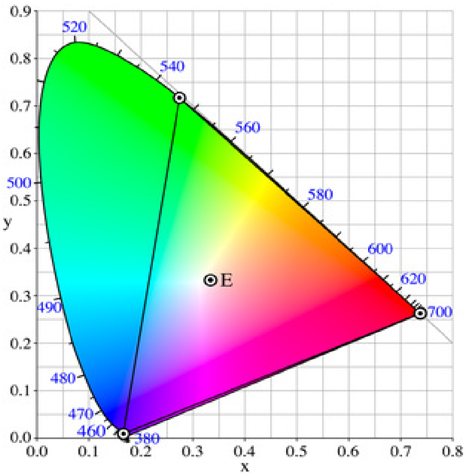


Fig. 2. The CIE 1931 colour space chromaticity diagram with wavelengths in nanometers, in RGB gamut.

to a physician determining a patient's optometric capacity, but they are not of practical significance to computer oriented tasks. Ideally, the colours included by the CIE gamut are infinite.

In computers, the chromatic model that is basically used is the RGB [11] according to which every colour occurs as a mix of Red (R), Green (G), and Blue (B). Measured with their wavelengths λ, these basic colours correspond to wavelengths of 700 nm, 546.1 nm, and 435.8 nm respectively (Fig. 2). For every pixel in true colour screen representation 3 bytes of information are used. Each of them, valued from 0 to 255 (2^8=256), defines the weight of participation of each of the three primary colours in the composition of the desired colour. The RGB curves are shown in Fig. 3.

With the RGB model, about 16 million of colours can be visualized on screen. However, a more thorough examination of the curves representing the primary colours in the RGB model shows a weakness in the representation of some frequencies in the optical frequency range. This weakness is localized in the Red curve, which takes negative values in some places of the wavelengths of the optical frequency range. This means that red

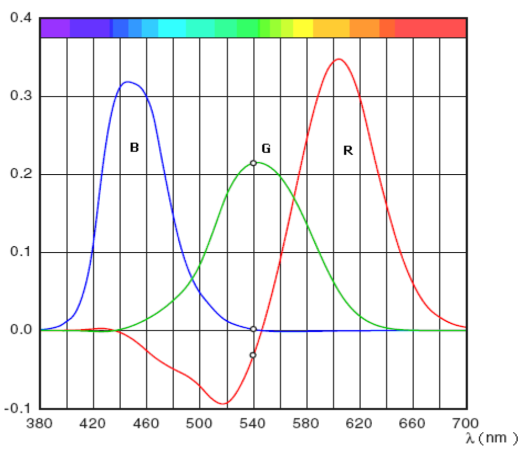


Fig. 3. RGB curves construct the rest of the colours.

has to be added to the monochromatic stimulus to make the match.

The above mentioned weakness makes the RGB model incapable of representing all real colours. In some sense, this is expected: real colours are by far more than the 16 million that computers may visualize, and it is impossible to transform all values from the continuous optical frequency domain to the discrete valued RGB domain. Indeed, the triangle in Fig. 2 shows the purely additive area of RGB, which constitutes the RGB gamut. The underlying reason for the RGB's model failure to represent all possible colours is the fact that the colour calculations are translated from the wavelength domain to the display domain.

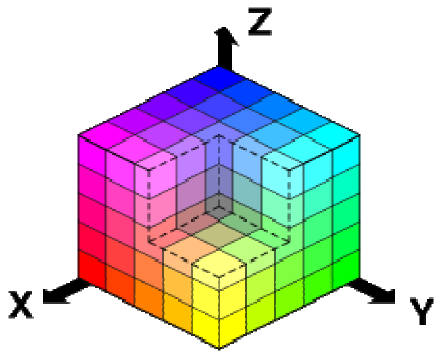


Fig. 4. The 3-D area defined by the RGB values, containing all the colors a PC may display (with a cutaway shown).

Although the theoretical approach to chromatic translations reveals the aforementioned weakness, it is clear that for practical reasons 16 million colors are far more than adequate in displaying colors (Fig. 4). Indeed, so many colors are more than human capacity to memorize colors. Furthermore, as we will see, they are more than the possible sound entities that may be used in sound to image transforms. So, the RGB color space, where every color is calculated following formula (4) will be adequate.

$$F = r\,\mathbf{R} + g\,\mathbf{G} + b\mathbf{B} \qquad (4)$$
$$r, g, b \text{ in } [0, 255]$$

Thus far, all the algorithms visualizing the colors of music [3] [5] take sound as a one dimensional signal, not taking into account the 'musical' perception of sounds which yields a second, 'hidden' dimension. Indeed, frequencies are interrelated, and although they remain discrete, in musical terms they have equivalencies and relations. For instance, note A_4 corresponds to 440 Hz, and it is the basis for tuning all musical instruments according to the well tempered scale of Western Music. The note corresponding to 880 Hz is of course another distinct frequency, but in musical terms it is somehow equivalent to A_4, being an *octave* higher: it is A_5. Therefore, music perception does not merely accept sounds as vectors $\boldsymbol{v} = (f, \Delta t)$, but seeks to establish relations between notes, defining the *intervalistic* conception of music.

Accordingly, notes form intervals which are the basis for the melodic dimension of music. As Aristides Quintilianus states: "Music is the science of melody and all elements having to do with melody" [38]. Therefore, the feelings and sentiments produced by music do not have to do with the notes themselves but with the intervals they form, yielding the melodic coloring of music.

2. Chromaticism: The colouring of Music

Chroma (the Greek word for *color*), as is generally defined, is the aspect of any object that may be described in terms of hue, lightness, and saturation [9]. The term chroma is strongly associated with the arts of music, especially with comparative musicology.

The term "chroma" was first defined in Ancient Greek Music [17] [40][41][42]. From there, the separation in "chromatic", "harmonic", "melodic" and "diatonic" entities has evolved for the Western music paradigm [25].

Likewise, the characterization of a musical hearing as chromatic or non-chromatic consists strongly in its association with psychoacoustic phenomena, e.g. one particular artist may *color* a musical piece using his voice, while other artists may not [34]. One can realize, while listening to a composition, that the stronger feelings this causes to us, the more chromatic it is. The inverse statement is also true. Psychoacoustics theories are used for corresponding musical segments with colors in the results section.

Next, we juxtapose some of the potential uses of the term chroma in several works. From a scientific point of view, chroma is one of the attributes of sound. The rest of them are: tonal height, density, direction and mass [16]. The tonal height or pitch can be conceptualized as a bidimensional quality, reflecting both the overall pitch level of a tone (tone height) and its position in the octave (tone chroma). Shepard [32] has defined with chroma the note's position within the octave and has created a nonlogarithmic pitch helix, the *chroma circle* that clearly depicts octave equivalence. This has led to rather complex pitch-space representations in which the chromatic tone scale, the circle of fifths, octave circularity and other properties are all accounted for. This approach perceives chroma as extension to the concept of tonality. In contemporary literature, chroma is not to be confused with *timbre* (=sound color) . Timbre has been defined by the American Standards Association [1] as "that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar". Sundberg [34] has added emotional coloring using tone categorization, while Juslin [15] has mapped musical expression cues of basic emotions.

2.1 Purpose and objectives

None of the above statements will be further used throughout this paper, since the purpose of this research is to provide the web of ethnomusicology with an index of background acoustic variability, using chroma as *a musical genus discriminator* [7] [42]. Genuses or species [39] are not perceived as contemporary genres like hip-hop, disco or jazz; therefore the chromatic index is not a genre discrimination method, like the one proposed by Tzanetakis and Cook [35] but mainly an intervallic systems classifier beyond the Western musical paradigm, introducing metrics for the progress of the concept of chromaticism. So, we would rather classify musical pieces into more or less *chromatic genres*. The approaches and definitions, used in this research, are described in the next 3 subsections.

Many attempts to sound modeling with colors have been done, in term of correspondences between the physical dimensions of sound and color [4] [24]. Giannakis & Smith [6] provide a review of auditory-visual associations as these have been investigated in computer music research and related areas.

Amongst the most popular are the ones used by media players. For instance, Microsoft's Media Player when playing sound instead of video files in its effective visible area depicts impressive real time visualizations that depend on the temporal characteristics of the reproduced music peace; however, they fail to depict the melodic structure of the sound heard.

In this paper's proposal, an effort to correlate music chroma with musical emotion is necessary, since music and colors are associated with emotions. The melodic progression creates *chromatic impression*, which in analogy can be depicted as a simultaneous *chromatic progression*. This progression, joint with psychoacoustics theories, results in the proposed chromatic graphs (see Section *5. Experimental Results*). Although measuring emotions continuously is open to criticism, Schubert [31] has modeled perceived emotion with continuous musical features. Chroma can be pertained as a continuous musical feature

2.2 Theoretical Approaches to Musical Chroma

Chromaticism in music is the use of notes foreign to the mode or diatonic scale upon which a composition is based, applied in order to intensify or color the melodic line or harmonic texture (*normal definition in Western music* [14]). Barsky [2] discusses about the two systems of chromaticism: (a) melodic chromaticism (*horizontal*) and (b) chordal chromaticism (*vertical*). In Ancient Greek music, the term referred to the tetrachord, or four-note series, that contained two intervals like semitones. It is remarkable that not all-ancient or medieval music had a compass as wide as an octave ([7] [17] [39] [42]). Later, in European music, the term "chromatic" was applied to optional notes supplementing the diatonic (seven-note) scales and modes, because these notes produced half-tone steps that were extraneous to the basic scale or mode. A full set of chromatic tones added to any diatonic scale produces a chromatic scale, an octave of 12 semitones [13].

Based on the previous sections, and taking also into account Oriental scales, it is essential to sub-divide the spaces between notes in a more accurate way than the 12-tone subdivision. This subdivision exists in the aforementioned modes and one can impulsively perceive, listening to relative scales, chroma, comparing them to Western modes [27]. This observation leads to the conclusion that the essence of chroma is associated with the intervals between notes, and more specifically with the several intervals unequal to the tone (half – tone, 3-half-tone, quarter-tone etc) [13].

Musical instruments, like the classical piano, can execute a particular melody with limited (little) chroma. This extracts from the fact that the piano can only produce discrete frequencies of sound (12 frequencies per octave), so the chromaticity of the piano is specified only in terms of unrelated to the specific scale notes. Consequently, in this case the concept of chroma coincides with the terminology of Western music.

What happens, however, in the case of the violin or the great "instrument" of human voice? Things here are much more complicated, since the violin or human voice can produce continuous sound frequencies without limitations. It is well known that singers especially do not maintain a single pitch constant throughout a note, instead using techniques like portamento and vibrato [33]. Moreover, the intervals between notes can be of any distance, not just multiples of the half tone, as with the piano. These special intervals give more chroma to the sound (see Fig. 5). Finally, this paper handles only melodic intervals, since melody is more prevalent than harmony in world musics [26].

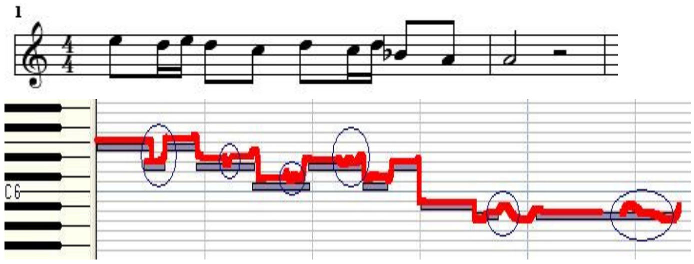


Fig. 5. A segment from the traditional song "Miserlou": The musical human interface of chroma in staff notation, in haptics, and its fundamental frequency (F0) perception from the corresponding vocal performance. The latter, marked as a red line, bears hidden chroma.

2.3 Definitions: what is "chromatic" after all?

The concept of chromaticism is strongly associated with our perception of music. The research presented in this paper is only focused on horizontal chromaticism (melodic line). In an effort to reach a definition that covers all the discussed aspects of chroma in music the following have been concluded:

1) *Chroma is mostly associated with the music intervals.* The interval sizes may add an extra chromatic dimension in a specific melodic line. While a specific interval may cause a chromatic perception in a musical piece, in some other may not (see Fig. 7).
2) *Each scale has an inherent chromaticity, which we call **Scale Chroma by Nature.*** "Scale Chroma by Nature" is also associated with the intervals it contains and their distribution. This kind of chroma is not to be confused with each sound personal chroma. "Scale Chroma by Nature" provides the listener with the general perceptive impression that the scale gives in a musical piece. For example, the general impression of a major scale in a song is happiness (which does not mean that the same song cannot be momentarily sad), while a minor scale induces in general melancholy. This means that a minor scale has a different "Scale Chroma by Nature" from a major one. We provide a way of measuring each scale's "Chroma by Nature".
3) *The fundamental basis of the developed metric for "Scale Chroma by Nature" is the occurrence of intervals other than whole tones (200 cents) and intervals that are not multiples*

of whole tones within a scale. It returns to the original meaning of the scales some music uses being “chromatic” (rather than “diatonic” or “enharmonic”), extending this to allow scales to be more or less chromatic.

4) *A sound in a musical piece is defined as “chromatic”, as far it is produced out of intervals, different than the ones, which the scale that the musical piece is written to contains.* This definition also encompasses the occurrence of any sound with frequency irrelevant to the discrete frequencies of the scale in the musical piece. This is the normal definition of the term (stated in section 2.2) and should not be confused with the definition of *Scale Chroma by Nature*. A scale can contain itself chromatic notes and this may result in a greatest “Scale Chroma by Nature”, but since they are taken into account in the Scale Chroma Measuring algorithm, they are considered notes of the established scale within the piece. So, if a note of this kind is encountered through the melody of the piece, it is no more chromatic in context, which means it does not add any extra chroma to the one of the scale and furthermore, of the musical piece in general (see Fig. 6).

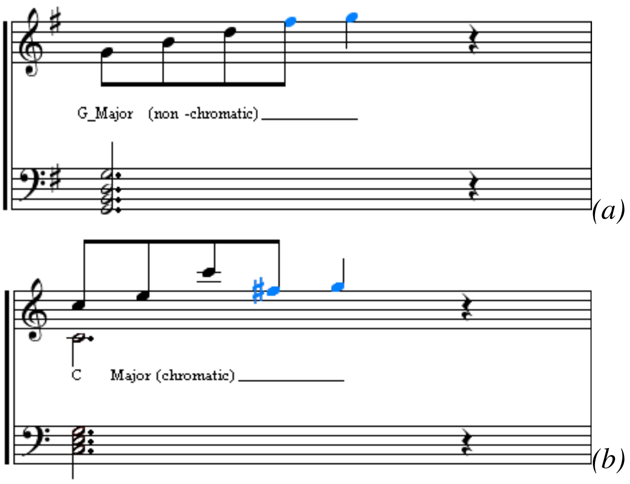


Fig. 6. (a) The interval F#-G does not add any chroma ($\chi = \chi^o$) to the musical piece, which is written in G – Major (χ^o=1.286). (b) The same interval adds more chroma ($\chi > \chi^o$) to the musical piece, which is written in C – Major (χ^o = 1.286)

5) *In proportion to the distance of the interval, that a sound creates with the precedent one, it can be estimated, <u>how much</u> chromatic this sound is*. Certain metrics are proposed for this.

6) *The progression of the melodic line of a musical piece results in a corresponding progression in the chromatic perception of the piece*. Therefore, if we associate our proposed metric χ *(chromatic index)* with the human chromatic perception, we can represent the chromatic progression over time in either a two – dimensional graph, or a “chromatic” strip, which is related to the notion of “color” in music.

The approach that is followed in this paper, in order to measure chroma in music, according to the previous definitions – explanations is:

- Each scale bears a definitely measurable “Scale Chroma by Nature”, which is symbolized by χ^o.
- Each piece can add or eliminate chroma due to the following factors:

I. Use of notes outside the established scale.
II. The melodic line progression.
III. Rapidity (this factor affects only the saturation of a color, related to chroma, in the visualization process).

These 3 factors apply on the *chromatic index* χ of a musical piece.

3. The Alphabet

The notation in the current paper is the proper staff notation of Western music with the addition of the half-flat sign 𝄳 and the half-sharp sign 𝄲 from the Arabic music. The half-flat sign (𝄳) represents some frequency between one note and its flatted one, while the half-sharp sign (𝄲) represents some frequency between one note and its sharp one. Using these extra symbols, the minimum spaces are the quarter- tones (see Fig. 7).

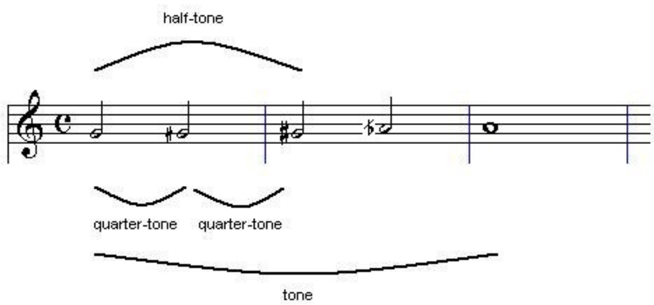


Fig. 7. The notation for microtonal staff symbolism.

This symbolism is an approach to recording variant musical hearings in the Western music notation. Greater subdivisions could be used in lots of cases, because of the peculiarities in notation of Western and Oriental music, for more accuracy in finding chromatic elements [7].

3.1 Fuzzy Frequencies Correspondence

In Oriental music, a maqam is a sequence of notes with rules that define its general melodic development. The nearest equivalent in Western classical music would be a Mode (e.g. Major, Minor, etc).

Many maqams include notes that can be approximated with 'quartertones' (using the half-flat sign 𝄳 or the half-sharp sign 𝄲), although they are rarely precise quarters falling exactly halfway between two semitones. Even notes depicted as semitones may include microtonal subtleties depending on the maqam in which they are used. For this reason, when writing for instance Arabic music using the Western notation system, there is an understanding that the exact tuning of each note might vary from each maqam and must be acquired by ear.

For computer music predicates, there is need to precisely match notes with accurate frequencies. The most frequently used formula for calculating the frequency of a given note is:

$$f=f_o.2^{(c/1200)} \qquad (5)$$

where f is the frequency of the given note, f_o is the reference frequency, and c is the pitch shift in cents. 100 cents are a semitone and 1200 cents are an octave [23]. Therefore, it follows that doubling the frequency of a note puts it up and octave and halving the frequency of a note puts it down an octave. For example, if we know that the frequency of C_4 is 261.63, and we want to find the frequency of D_4, we set c=200 (interval of a whole tone) and f_o=261.63, so the desirable frequency is

$$f=261.63\ 2^{(200/1200)}=261.63 \qquad (6a)$$
$$2^{(1/6)}=261.63 \times 1.122=293.66 \qquad (6b)$$

In order to find the frequencies of quarter-tones we set c=50 and use as reference frequency the note that was calculated before (in other words: we use the formula: $f=f_o.2^{(50n/1200)}$ for all integers n. Table 1 shows a small part of this microtonal distribution (A_4 is tuned to be at exactly 440 Hz):

TABLE 1
Reference chart of quarter-tone frequencies.

Note	C_4	C𝄲$_4$	C#$_4$	D𝄳$_4$	D_4
Freq(Hz)	261.63	269.29	277.18	285.31	293.66
Note	D𝄲$_4$	D#$_4$	E𝄳$_4$	E_4	...
Freq(Hz)	302.27	311.13	320.24	329.63	...

However, in Table 1, only a set of discrete frequencies has been defined. The rest frequencies need to be considered in order every sound to be symbolized. After evaluating the middle frequencies (c=25), every possible frequency corresponds to a specific note, which is bounded by a minimum and a maximum value and can be easily represented in a computer application. The frequencies between these values, seen in Table 2 (deriving from the utilization of the formula $f=f_o.2^{(50n\pm25/1200)}$ for all integers n), are slightly different. Although research reveals variations, a reasonable estimate of the Just Noticeable Differences (JND) in pitch is about five cents [30].

TABLE 2
Microtonal spectrum thresholds (intervals of quarter-tones).

Note	Low threshold	High threshold
C𝄲$_4$	265.43	273.208
C#$_4$	273.208	281.217
D𝄳$_4$	281.217	289.457
D_4	289.457	297.937
D𝄲$_4$	297.937	306.667
...	...	...

4. Problem Formulation

The procedure followed for the ascription of colors for a piece of music has 5 steps, depicted in Fig. 8. Step 1 aims to isolate melodic motives in a piece of music so as to search for chromatic elements in it. MIDI and audio files (WAVE, MP3) were used and processed in different ways. In step 2, the isolated melody corresponds to a specific scale or mode, recorded in a "Scale Bank", using a simple algorithm. Every scale in this database bears an initial real number χ^o, which determines its "Scale Chroma by Nature". In step 3, melody is separated in segments, in order to process it piece by piece. In step 4, elements that add chroma to the given melody are found and analyzed, resulting in some real values. These numbers, correlated with χ, affect the "color map", and finally the chromatic graph of the musical piece is estimated in step 5.

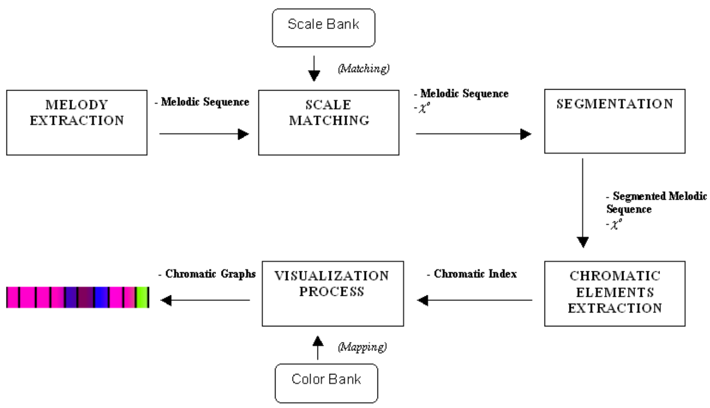


Fig.8. Problem formulation task analysis diagram.

In the early stages of our research, the whole analysis process was manual. We have used several assisting computer application on this account. However, we have currently developed an integrated tool for chromatic analysis: *MEL – IRIS* (= "Melodic Iris"), which automates the whole process. It has been programmed using C++ user interface routines over Matlab analysis functions. The aim of this paper is to present the theoretical background of our work and not technological details on MEL-IRIS, although some discussion about it qualifies as necessary.

An important observation for the framework of MEL-IRIS is that the whole analysis process is almost absolutely serial. This means that one step's output is the input to the next step. The instant consequence is that each step's function is autonomous and self – independent. Therefore, each function can be treated in a different way and modified without affecting the total system's performance. This is really important, since MEL-IRIS executes functions that come under critical research areas of growing interest, where an accepted integrated solution of the problem has not yet been found. Such fields are, for example, the melody extraction out of Audio files, the scale finding from an Audio musical piece or the segmentation of melody. Because the essence of the research in music chromaticism lies not on these pieces, but on the extraction and vizualization of chromatic parameters, their implementation has been carried out using elementary algorithms, based on some important aspects of the corresponding research area. However, there is the capability of easily replacing them with more complete, documented and audited research outgrowths (as it was mentioned before).

4.1 Input Management

It is obvious that the procedure for melody isolation is non-identical for MIDI and audio files. The separation of melody from accompaniment is an area of current research in Music Information Retrieval. Recently several predominant pitch detection models and algorithms have been proposed for polyphonic audio [10] [18] [20].

4.1.1 MIDI files

In MIDI files it is simple for the melody to be isolated, since in a well-orchestrated MIDI composition, melody can be usually found in some track, which often bears the label "melody". We have used Cakewalk Music Creator 2003 and easily extracted melodies from several MIDI files. In some cases, greater effort was needed in order to recognize and isolate the melody, e.g. in some 1-track piano pieces. Nevertheless, no special difficulties were encountered at this part of the project.

4.1.2 Audio files

Things were not that clear as when analyzing audio files, since scores could not be directly extracted from the musical piece. Although in our early experiments we have used Sonic Foundry's SoundForge 7 and MatLab 7 for sonogram analysis, the development of MEL-IRIS led to an automatic FFT transform on audio signals and peak selection out of them. In recordings where melody (or singer's voice) surpassed accompaniment, we have managed to get (in a very good approach) the frequency sequence of melody. Spectral analysis of music has yet been discussed in several works [19] [21]. The analysis proved to be easier in recordings with little (or without) accompaniment, while in 'tough' orchestrations difficulties were encountered in configuring loudness and display range settings on the FFT sonogram. A detailed description of those settings configuration disqualifies as necessary at this paper. Directly related to this is the query of how many simultaneous melodies may be transcribed by a skilled human transcriber. This is the "Principle of Limited Density" for which Huron [12] states that "…If a composer intends to write music in which independent parts are easily distinguished, then the number of concurrent voices or parts ought to be kept to three or fewer."

The results of step 1 analysis for one MIDI and one audio file are shown in Table 3 containing the frequencies sequence for the first 9 events of each melody. These frequencies (which are considered as melody notes) are chosen for extraction according to some clues that music perception research provides us. Typically, the highest-pitch notes would be classed as the melody notes unless they are monotonous. On the other hand, the lowest-pitch notes usually correspond to drum percussion, so they are ignored. For other notes to be identified as the melody, various compositional tricks need to be applied such as making it much louder than the accompanying notes and making use of a single timbre throughout the melodic phrase [36]. On that case, the sequence of frequencies is produced with sampling of frequencies that bear the highest volume (the darkest peaks on the 3-D graph) at a specific time. We use very short pre-defined time intervals for the sampling (250 ms by default).

4.2 The Database

After the ending of the analysis process on a musical piece, MEL-IRIS stores the results in the "MELIRIS" database, which is structured on Microsoft SQL server.

Details about the database organization and the relationships between the database fields can be seen in Fig. 9 [37].

In particular: the name of the audio file, its destination and the duration of the musical piece in milliseconds are stored in the SongList table, which is the main table for searching inside the database for results by the song name, the song duration or the song destination.

The table SongsDetail is the detail table of SongList and contains information about the average chroma, the tone, the origin, the file format (midi, mp3, wav) and the scale that the musical piece corresponds to. Because of the existence of multi-channel musical pieces, an extra field "Channel" was added. This field contains integers (e.g. 1-16 in case of MIDI files). A song search, based on the average chroma of a song (or just a channel), can be run on the SongsDetail table.

As it can be seen in the Data Diagram (Fig. 9), the table SongKaliskope is the detail table of SongsDetail. This table contains the colour information for each channel (R,G,B and Chroma) and each song segment's duration (Length, StartTime and EndTime). The role of the table SongKaliscope is double. First, it provides the necessary information for the colouring of a musical piece, while the media player executes it, and second, it helps the in-depth search of a song based on the chroma in each segment per channel.

The SongMaster table consists only of the ID field, which contains values from 1 to 5. These values correspond to the following chromatic categories: 1 = "Very Low Chromatic", 2 = "Low Chromatic", 3 = "Medium Chromatic", 4 = "High Chromatic" and 5 = "Very High Chromatic". The SongMaster and SongList tables are master tables of SongsDetail.

Finally, the ScaleBank table is the data bank for the correspondence of a musical piece with a scale. An important point is that he user can add more scale values in the application, in order to enrich the Scale Bank and better approach the correct scale correspondence.

Two problems regarding the database came up while developing the application:

The "MELIRIS" database format changed from Paradox to Microsoft SQL server, in order for the program to be later used in a network database, where the users would be able to look for and exchange musical pieces in proportion to their chroma.

The whole database was totally reorganized, in order for the application to support multi-channel musical pieces. This additional capability also resulted in the creation of the channel field and the SongDetail table.

4.3 The Method

Initially, we tested the analysis tool on the server of Multimedia Lab of the University, which hosts over 2 millions (classified by genre) songs, in MP3 format, from all over the world. 16 students (which we consider as a satisfactory number for our primary results) aging 18-25 years old helped the research with their opinions (10 students of Computer Science, 6 students of Music). They were asked to create their own colour sequences (in case they didn't accept our default sequence) and afterwards run 10 songs of their choice on the server.

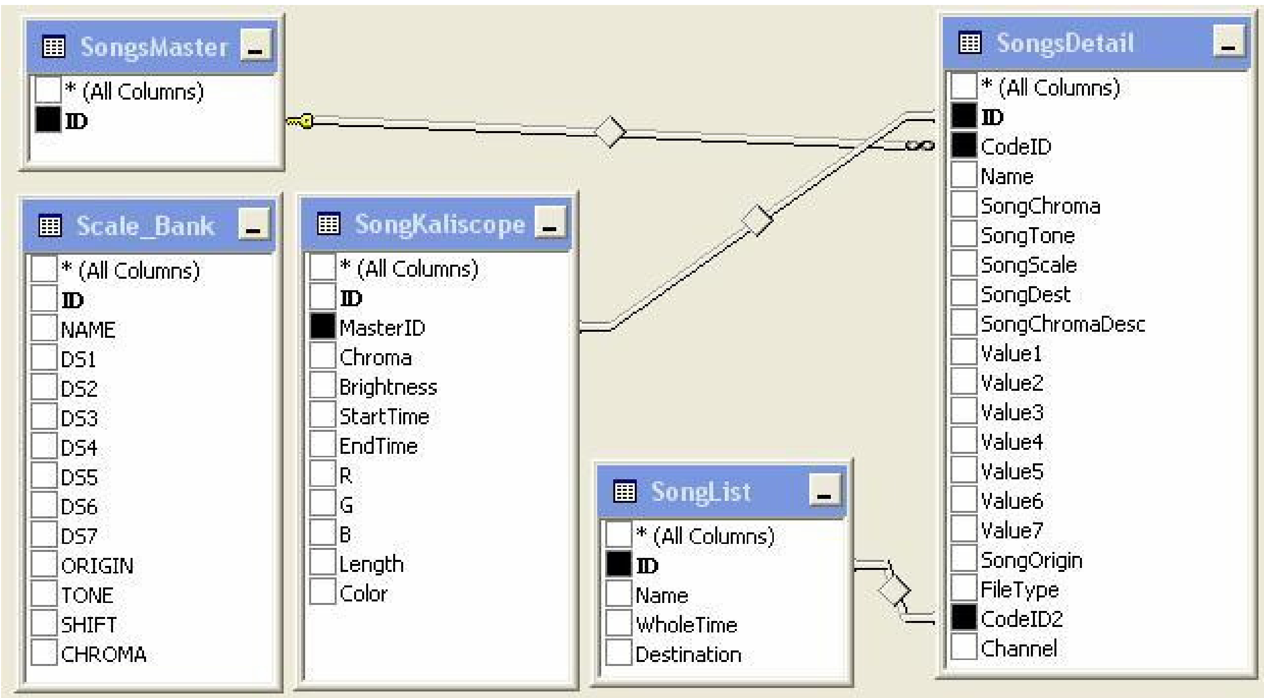


Fig. 9. Organization of MEL-IRIS database.

In this paper, we present the results form the chromatic analysis of a sample of 407 MP3 songs that were randomly chosen and initially scattered in 12 genres.

Due to space constraints we cannot display or discuss the full statistics for the sample. We will thus pick up a few examples, in order to demonstrate some fundamental functions of MIR using colours. We will (i) examine the common attributes of the songs in each of the categories mentioned before, (ii) apply filtering queries on the sample, and (iii) try to detect similarities (from a psycho-acoustic and a musicological perspective) in songs that resulted in congener chromatic graphs.

The full experimental results are available for further exploration at:
http://www.csd.auth.gr/~dpolitis/MEL-IRIS

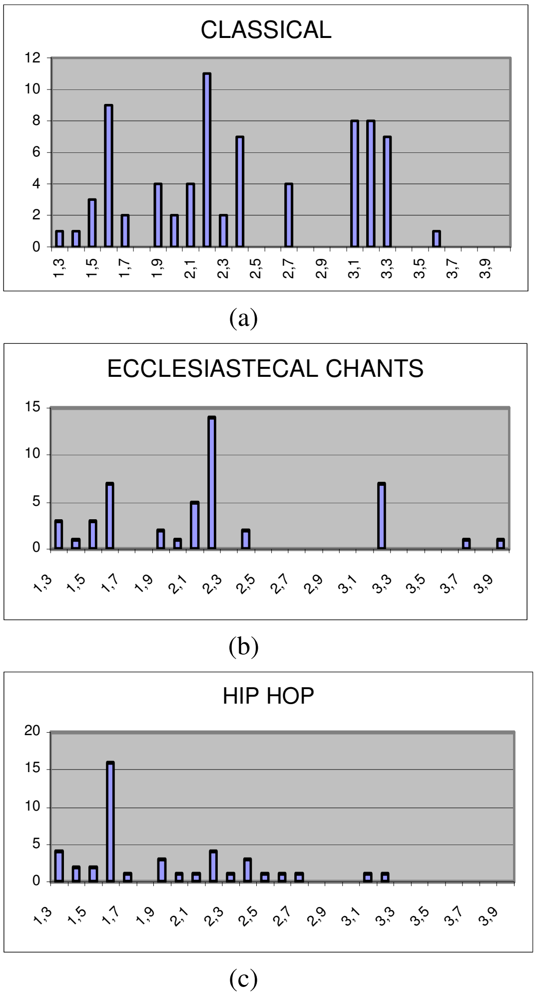
4.4 Experimental Results

Table 3 shows summarized statistics for each of the 12 genres of the sample. Although some genres contain only a few songs and are therefore not recommended for general conclusions, we can make some observations on the numbers.

Table 3. Summarized statistics of the sample.

GENRE	# Songs	Ch. Avg
Classic	75	2,413
Dance	7	1,888
Hip Hop	44	1,890
Metal	13	1,856
Pop	51	2,127
Rock	15	1,869
Greek Old Classics	15	2,517
Greek Traditional	4	2,232
Rebetico	53	2,085
Instrumental	50	2,083
Ecclesiastical	47	2,196
Ethnic	33	2,061
TOTAL	**407**	**2,2**

Taking into account the genres that contain over 30 songs, we can observe that the most chromatic genre is classical music. In Fig. 10(a), we can see that there is a great variety of chromaticism in the classical songs of the sample. In contrast, the hip hop genre (the less chromatic from the considered genres) shows no such variation with the most of the tested songs belonging to an orange tint of about χ=1,6 which corresponds between "Very Low Chromatic" (χ=1) and "Low Chromatic" (χ=2), as seen in *Fig. 10(c)*. This is normal, because hip-hop music is more rhythmic and less (or not at all) melodic and creates static little chromatic impression to the audient. Fig. 10(b) shows the songs distribution of ecclesiastical chants, which is a very chromatic genre. We can note here that it was the only genre, where chromatic averages greater than 3,5 appeared (with an exception of a 3,6 occurrence in classical music).



(a)

(b)

(c)

Fig 10. Songs distribution from the chromatic analysis.

4.4.1 Queries

The database has been created for song clustering based on their chromaticism, which is obtained from the MEL-IRIS tool. Therefore, the database is useful for chromatic and statistic search on the server's songs.

In particular, the user can search for any genre and find chromatic similarities in terms of percentage coverage either in a musical piece's segments, or in all processed songs. Moreover, chromatic analysis diagrams of the pieces in terms of time can be extracted. MEL-IRIS presents the percentage of each colour's occurrence within a piece and also classifies each song according to its average chroma. Finally, the user is given the option to directly reproduce similar patterns of songs for further observing.

Some of the queries available on MEL-IRIS are:

- Find the top- k songs whose total average chroma <χ>tot. is χ.
- Find all the songs whose average chroma is between χ1 and χ2.
- Find all the songs, which have a tint of colour in a percentage greater than/less than/equal to the n % of the song.
- Find the n most similar (in terms of colours) songs to the song.

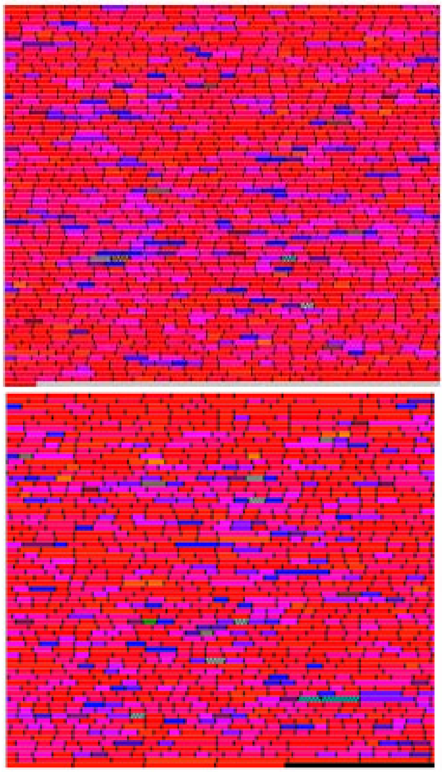


Fig 11. MEL-IRIS visual display results of the songs: "How you gonna see me now" – Alice Cooper (top), and "The trooper" – Iron Maiden (bottom). Both songs belong to the 'Metal' genre and have similar chromatic graphs (in terms of colouring).

The user can produce queries applying values on the variables of the queries, where:

k: integer
χ, χ1, χ2: float
colour: string (e.g. pink, blue etc.)
n: integer (range: 0-100).
Song: song name

For example, the result of the query "Find the top-3 songs whose total average is 1,3" in our database was:

- Smell of Paradise (Sa Trincha)
- Adios Andalusia (Eric Fernandez)
- How fare this spot (Sarah Brightman)

A second demonstration query on our sample was "Find the 3 most similar songs to the song 'How you gonna see me now' (Alice Cooper)". The number one returned song (the best match) was 'The trooper' (Iron Maiden), which also belongs to Metal songs. Fig. 11 presents the chromatic graphs of the two songs, while Fig. 12 shows their colours distribution. The similarity is obvious.

The graphs in Fig. 13 show the chromatic progression of χ in all the three metal songs returned from the query. The value range is almost identical (the third song is 'Laguna Sunrise' – Black Sabbath).

In the tested sample the statistical averages state that 78% of the songs in the same genre (e.g. pop, rock) showed the same average chroma on their graph in a percentage of about 59%. For example, 70 songs in our sample belong in the rock-ballad genre. 74% out of them had pink as their average colour in a percentage of 60%.

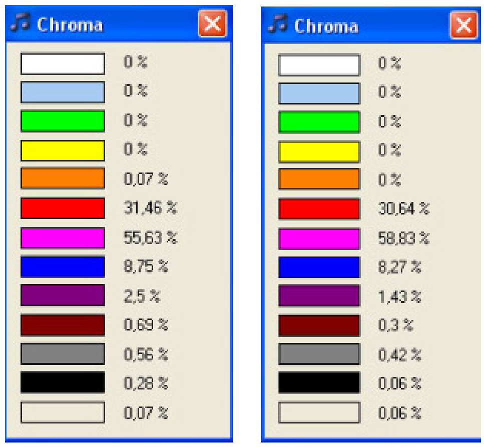


Fig. 12. Similarity in the percentages of colours for the two analyzed songs of Fig. 6.

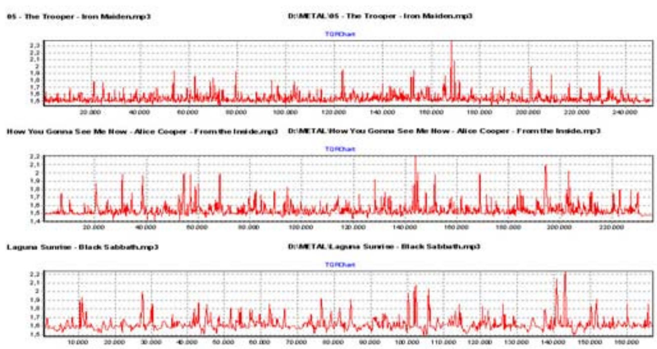


Fig. 13. Sample graphs of the χ progression over time for three songs of the same genre.

4.4.2 Similarity Patterns

Among the several observations on the chromatic graphs is that several similarities between a song's patterns occurred. The similarities were obvious from the colour and the size of the segments. This is absolutely natural and predictable, since a song usually has both identical repetitions (musical phrase repetition – "physical refrain") and slightly varied repetition (musical phrase variation – "fake refrain").

In Fig. 14, we can see part of the chromatic graph of the song "Say something" (James). The checked 3 lines comprise part of the refrain. Watching carefully on the first and third line, we can observe two exactly similar patterns.

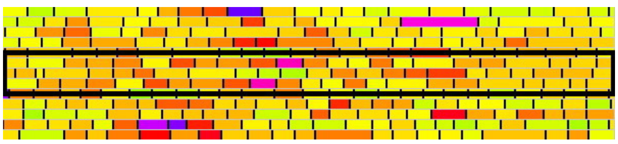


Fig. 14. Similar patterns extracted from the song "Say something" – James.

4.4.3 Interviews

According to students' opinions (in a short interview during and after the experimental task), the produced colourful stripes were satisfactory for them in a percentage of 96%. In particular, one student stated, "the feelings arousing from the visual representation are too close to the pieces' aesthetics". As a whole, the users were amazed by the musical piece segmentation, as it proved to 'conceive' (in an algorithmic way) the musical alternations, which they acoustically perceived.

It is remarkable that the users observed as a whole that in many pieces of the same genre occurred a certain degree of similarity in their chromatic ascription.

Another experiment was materialized with the students: We showed them 10 different chromatic graphs from several genres and one predefined colour sequence (not the default). Afterwards, we asked them to recognize which graph corresponds to each of the 10 songs that we had them to listen in a random order. The results were very successful. This proves that the chromatic stripes can really act as a significant digital signature of a song. Our stripes database (which successfully indexes the digital music library) could further be used by anybody worldwide for searching music that match a specific colour sequence or a music sample.

5 Image to Sound Conversion

Before describing the methods for auditory display of colourful images, some definitions should be apposed.

The concepts of "*chroma*" (which is the fundamental concept that governs this research) and chromaticism have been thoroughly discussed in foregoing papers [28] [29] and by several authors [2] [7]. The basic principle is that the chromatic perception of music is affected very much by the intervallic distances between notes and not the pitches themselves. Indeed, we can estimate **how much chromatic** a musical scale or a melody is by using the *chromatic index* χ [28]. This certain variable is the basic component for creating music from images in the present paper.

We invented the term '*chromatic bricks*' in order to describe the units with which a complete music piece can be created from colours. The composer places colourful bricks (just as a bricklayer), which constitute as a whole the *chromatic wall* (Fig. 15). A chromatic brick is to all intents an oblong (filled with a specific colour) that represents a particular musical phrase (a sequence of notes of the melody). Each brick contains the following information: its colour corresponds to a χ_i value ($1 \leq \chi_i \leq 2.2$), which is translated to certain emotions; and its length, which defines the time of the particular musical phrase. In the present paper, durations are considered as length ratios between bricks and not as absolute timings. All the bricks as a whole (that is the chromatic wall) represent the entire melody.

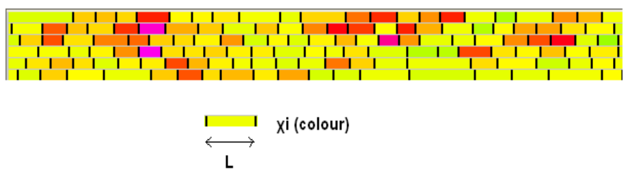


Fig. 15. A Chromatic Wall consists of chromatic bricks with length L and a chromatic value χi, which corresponds to a certain colour hue.

5.1 Algorithmic Production of Melody using Self-Created Bricks

According to this method, the composer has to build the chromatic wall by creating and putting bricks in place by him. The attributes that a brick needs to be comprised of are: chroma χ and duration of (these values are used as input of the algorithm for melody extraction). Previous to the beginning of bricks creation, the composer has to define: which scale shall his piece be written to (in order to define Scale Chroma by Nature χ^0, which corresponds to the fundamental chroma of the melody) by choosing a scale from the Scale Bank [29], the tempo of the piece (in order the melody to be correctly transcribed to staff notation), and the first note of the composition (which is the basis for the calculation of the first brick's chroma). The first user-defined note should constrainedly belong to the chosen scale.

After defining χ^0, tempo and the first note, the first brick (**χ1,d1**) should be created (**χ1** is its chroma value, and **d1** is its duration). Because of the calculations' complexity, the presented algorithm is oriented exclusively towards the χ variable, taking little into consideration the duration factor. Duration is counted in terms of notes values for simplicity. That is: ♩=1, 𝅗𝅥=2 etc. For instance, the brick (1.4 , 0.5) is a segment containing notes with values equal to an eighth (♪) and orange as its colour. Data modulation, so as real-time durations (in ms) is accepted, is under consideration for future research.

Chromatic synthesis with musical bricks uses the reverse method of chromatic analysis [28]. However there is an important issue here: although a musical piece is analyzed into one and only chromatic graph, a chromatic representation could result to different melodic sequences, which can be equally perceived in terms of feelings. For this preliminary proposal, 10 basic rules are used from the big list of rules for chromatic analysis with MEL-IRIS [29]. These rules are related to the use of notes that do not belong to the chosen scale, and therefore cause the notion of chromaticism (*Table 4*).

On the basis of these rules, we observe that the first four rules concern the χ increment; the next five rules concern the χ decrease, while the last rule is about the same χ value (the brick bears the same colour to the previous brick)[1]. Consequently, it is proper to use the first four rules in case of bricks with greater χ than the previous brick's χ. Likewise, rules 5 – 9 are applied to bricks with less χ than the previous brick's χ. Finally, the last rule is triggered whenever a similar (in terms of colour) brick to the previous one is created.

Let a brick contain n musical units[2] ($m_1,m_2,\ldots,m_n$). Each musical unit is assigned to a chroma value χmi (for $i=1,2,\ldots,n$) based on the interval which is created with the previous musical unit (according to the rules of Table 1). The chromatic index of brick j (χ_j) is equal to the average of χm_i ($i=1,2,\ldots,n$) of the musical units it contains:

$$\chi_j = \frac{\sum_{i=1}^{n} \chi_{m_i}}{n} \tag{7}$$

Table 4: Rules for the chromatic variable's χ transition in the colour space of an image.

Rule	Intervals	χ transition	Constraints
1	Chromatic semitones	*1.01	-
2	Chromatic 3/2-tone	*1.03	-
3	Chromatic quarter-tones	*1.04	-
4	Part of chromatic scale (N notes, N≥3)	*(1+0.01*N)	-
5	Chromatic integer multiples of tone	%1.005	-
6	Chromatic tones	%1.01	-
7	Retraction of chroma	%1.01	$\chi \geq \chi^0$
8	Retraction of chroma (3/2-tone)	%1.015	$\chi \geq \chi^0$
9	Same note repetition	% 1.02	
10	Accepted Scale Intervals	-	-

However for each χm_i ($i=1,2,\ldots,n$) stands

$$\chi_{m_i} = f\left(\chi_{m_{i-1}}\right) \tag{8}$$

and more specifically:

$$\chi_{m_i} = \chi_{m_{i-1}} \cdot k_i \tag{9}$$

where

$$k_i = 1 + 0.01 \cdot N_i \tag{10a}$$
$$\left(N_i \in Z^+ - \{2\}\right)$$

if it is about the rules 1-4, or

$$k_i = \frac{1}{1 + 0.005 \cdot N_i} \tag{10b}$$
$$\left(N_i \in \{1,2,3,4\}\right)$$

if it is about the rules 5-9.

The sum of χm_i is equal to:

$$\sum_{i=1}^{n} \chi_{m_i} = \chi_{m_1} + \chi_{m_2} + \ldots + \chi_{m_n} \tag{11}$$

If the newly created brick bears a greater χ value than the previous brick ($\chi_j > \chi_{j-1}$) and the chroma value of the last note of the previous brick is λ, then (7) becomes:

$$\chi_j = \frac{\sum_{i=1}^{n}\left[\lambda \cdot \prod_{k=1}^{i}\left(1 + 0.01 \cdot N_k\right)\right]}{n}. \tag{12a}$$

[1] The table values are evident of psycho-acoustic experiments and have been finally selected because they match well with our colours – music correspondence. Farther analysis of the particular theory disqualifies as necessary in this paper.

[2] The term 'musical units' is used instead of 'notes', because of rule 4, which concerns more than a note. One musical unit is equal to a note for all other rules.

In case of $\chi_j<\chi_{j-1}$ (less χ value than the previous brick) equation becomes:

$$\chi_j = \frac{\sum_{i=1}^{n}\left[\frac{\lambda}{\prod_{k=1}^{i}\left(1+0.005\cdot N_k\right)}\right]}{n} \qquad (12b)$$

χ_j and λ are known constant values. The algorithm returns n and the N_i factors values.

5.2 Selecting Bricks from a Database

The second method for using chromatic bricks produces unique results, and not multiple possible sequences of notes, although it is more restrictive for the user.

According to this method, fixed bricks, which are stored in a database, are used. Obviously, the composer, other users, or even a random brick generator may create additional bricks and thus enrich this database. This method supports two kinds of bricks: *absolute bricks* and *relative bricks*. An absolute brick is defined in a different way from a relative one. Also, different notation is used to represent each of those kinds.

Absolute bricks have two musical elements explicitly defined: notes and their values (they may even contain rests). For example, the absolute brick of Fig. 16 is:

$\{ (G_4 , 1) , (C^{\#}_5 , 1) , (B_4 , 0.5) , (A_4 , 0.5) \}$

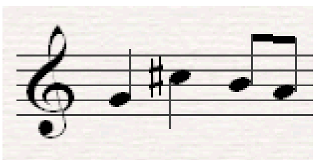


Fig. 16. An absolute brick in notation staff.

Unlike absolute bricks, relative bricks do not contain information about the absolute notes position, but only the relevant intervals between the notes. Values are also a part of the relative bricks. UDS notation [8] is deemed to be the appropriate notation for relative bricks. The format of a note in a relative brick is thus:

(UDS , #sem , v)

where:

UDS = { U (Up) | D (Down) | S (Same) }

#sem: the number of semitones in the interval which is formed by the note and the previous one (if UDS=S, then #sem=0, else #sem≠0)

v: the value of the note, (♩ = 1).

For example, the relative brick in Fig. 17 is denoted as:
{(U , 1 , 1),(D , 2 , 1),(S , 0 , 2),(U , 3 , 0.5),(U , 1.5 , 0.5)}

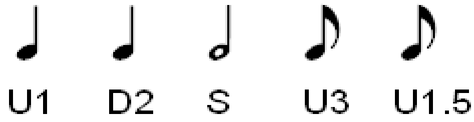


Fig. 17. A relative brick.

When the user is on composition mode, he/she is able to choose among any of the defined bricks in the database in any order. Each time a new brick is inserted to the chromatic wall, two events happen:

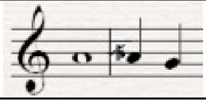
1. The relative bricks are converted to absolute bricks, since the last note of the last brick that was inserted into the composition allows the conversion. (Notice that this conversion is temporary, and not permanent. Relative bricks remain relative in the database.)
2. The chromatic average (χ) of each brick is calculated afresh, so as they can graphically appear bearing their colours for the user to choose.

It should be noted here that the chromatic value of each brick cannot be stored de novo in the database, because this calculation requires missing values that the user should first define (the scale with χ^0 and its key). The size that each brick possesses on the screen is determined by the values of the notes it contains. Moreover, at the time the user is prompted to select the first brick of his composition, only the absolute bricks are available. Relative bricks are not available since no previous note exists. Therefore, it makes sense why relative bricks are activated after the first brick's insertion. Fig. 18 shows the different representations of an absolute brick and two relative bricks in case of different λ in a different scale.

6 Conclusions

The visualization of an audio piece can be used both as an addition to the musical experience or as a unique "fingerprint" that marks and characterizes the file. The ability to easily identify chromatic patterns in a song enables its quick analysis and categorization, elevating the visualization as one of the strongest potential audio metadata.

The conversion of an image to sound based on the concept of chromatic bricks can be used to create unique musical compositions. The two methods described, the Algorithmic Production of Melody using Self-Created Bricks or the use of Database Pre-Stored Bricks, can cover the needs of elaborate and rapid conversion respectively. In addition this user-friendly approach greatly

Brick	Alphabet Notation	Staff (λ=1.3, A4, C-major)	G. B. R.* (λ=1.3,A4, C-major)	Staff (λ=1.7,C5, G-minor harmonic)	G. B. R.* (λ=1.7, C5, G-minor harmonic)
Absolute	{(G4, 1), (C#5, 1), (B4, 0.5), (A4, 0.5)}		(χ=1,2885) R=226,G=255,B=0		(χ=1,6813) R=48,G=0,B=255
Relative 1	{(U, 1, 1), (D, 2, 1), (S, 0, 2), (U, 3, 0.5), (U, 1.5, 0.5)}		(χ=1,3133) R=255,G=238,B=0		(χ=1,6969) R=8,G=0,B=255
Relative 2	{(S, 0,4,), (D,0.5, 1), (D, 1.5, 1)}		(χ=1,3262) R=255,G=222,B=0		(χ=1,734) R=44,G=0,B=212

*Graphical Brick Representation

Fig. 18. Different representations of bricks in different musical compositions. The chromatic index (λ) and the pitch of the previous note, as well as the scale, define the final graphical brick representation. Calculation of R-G-B values is done according to [4].

improves its usability through time, as additional bricks can be created, stored and used in future creations.

The use of a networked database in the proportionate tools like MEL-IRIS is considered necessary as it (i) easies the spread of custom conversion units (chromatic bricks) and (ii) accelerates the production of accurate statistics, multiplying the advantages of the audio-visual correspondence.

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