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Timbre and Technology: An Analytical Partnership

Stephen Malloch

What is music analysis? Ian Bent describes it as 'the resolution of a musical structure into relatively simpler constituent elements, and the investigation of the functions of those elements within that structure.'[1] What are the 'constituent elements'? Pitch is the element most often studied when a composition is analysed. Schenkerian analysis and pitch-class set analysis are both methods by which pattern and structure are sought in the realm of pitch. But what of the way a composer manipulates sound? Pitches must be sounded, whether in a performance or in a person's imagination, and composers usually make decisions about how they would like these pitches to be sounded. Yet, while music analysts are able to discuss pitch structures with a great deal of sophistication, their attempts to search for structure in the way pitches are sounded are few and often rudimentary. This study proposes a methodology for gaining analytical insight into a piece's timbral structure that is comparable to the precision and rigour that can be found in pitch analysis.

The manner in which pitched or un-pitched notes are sounded, I will call timbre. The American Standards Association (1960) states that 'timbre is 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.'[2] This definition of timbre has the disadvantage of defining timbre by what it is not. As a more positive definition, we can say that the aural information that we call timbre allows us to identify and classify a sound, and that this aural information

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1. Bent (1987): 1.

2. American Standards Association (1960): 45.

must consist of particular acoustic properties that are subsequently processed by our auditory system.

A tone produced by a musical instrument or voice consists essentially of three acoustic parts — starting transient (also called onset or attack transient), steady state, and decay. The starting transient consists of the very beginning of the tone, where there is rapid change during a very short period of time (for example, the length of the starting transient for an oboe note is around 15 milliseconds); the steady state portion is the more or less steady region of the tone, typically lasting between 100 ms and some seconds (though sounds produced by a single moment of excitation, such as those heard from the harp, piano and percussion, do not strictly contain steady state regions); and the decay is that portion of the tone that occurs after the player has ceased applying energy to create the sound.

Herman von Helmholtz, in the first major publication on music acoustics (1863), believed that timbre related only to continuous, steady state tones, with constant pitch and loudness. Since the work of Helmholtz, it has been shown that the starting transient is often a vital source of information for a listener's classification of an instrument, its brief duration belying its importance in this respect. While certainly not ignoring the acoustic information contained within the starting transient, I will not attempt to deal with the issue of how the starting transient can be analysed separately from the steady state in order to understand its particular contribution. This study attempts to find ways in which the timbral trajectories of compositions can be discussed. It is supposed that our impression of a piece's timbral trajectory, especially within the context of an ensemble sound, consists largely of the information contained in the steady-state portion of sounds, which, in an ensemble sound, combine to create an ensemble timbre.

In both the fields of music research and acoustics, a lot of work has been done over the past twenty-five years or so in trying to determine what the elements of timbre are, and how timbre may usefully be analysed. This study is very much part of this tradition. In particular, it attempts to answer the question: Can we find a plane of concepts and a vocabulary that allow timbre to be discussed and analysed within the discipline of music analysis with the same degree of rigour that has been brought to the sphere of pitch relations?

To lay the foundations for the new approach to timbre analysis to be presented here, it is necessary first to review some basics of the physics of sound, and the functioning of the human auditory system.

Virtually all scientific work on timbre has as its basis the work of Helmholtz, who in turn made use of an idea first put forward in 1822 by the French mathematician J. B. J. Fourier. Fourier found that a complex periodic wave form, that is, a complex vibration that repeats itself exactly after a certain period, may be represented as the sum of a set of sine curves, which are the simplest possible type of periodic motion. These sine waves are related to each other such that the frequency of the first is equal to the fundamental frequency, f, of the complex wave form (that is, it has the same repetition frequency), the second has a frequency of 2f, the third 3f, and so on, until all the details of the complex wave form are accounted for. Although a pitched musical sound is generally not exactly periodic, and un-pitched sounds are un-pitched precisely because they are non-periodic, it is still possible to analyse such sounds into their sinusoidal, or Fourier components, which can subsequently be displayed in a spectrographic analysis (for example, see figure 1). The quality of a musical sound depends almost entirely on our perception of its spectrum, which comprises its Fourier components — their frequencies, the way they are spaced (their differences in frequency), the way they change through time (though this issue is not directly addressed in this study), their amplitudes, and the way in which the components react with each other. The way in which the sinusoids 'fit together' — their relative phase — is of secondary importance in a musical context, and in particular is of secondary importance during the steady-state. Therefore, the effect of phase will not be addressed here.

It is important to remember that the representation of the physical properties of a musical sound in a spectrum analysis is only the beginning of understanding its timbre, for the sound is first processed by our hearing mechanism before we perceive it. Our hearing mechanism changes or 'weights' the components of the sound in various ways, and a number of mathematical models (based on the results of extensive perceptual experiments) have been suggested to estimate what happens to sound waves after they enter our ears. Thus, analysis of musical sound consists of two, distinct tasks — first, measurement of the physical properties of the sound (the results of which can be presented in a spectrum analysis); and second, the manipulation of this data in order that it might accord more closely with our perception. The first task is relatively straightforward. The second has often been neglected in the discipline of music analysis when acoustic analysis is incorporated. This omission severely limits the degree of music analytical insight that can be gained.

One of the first to address the problem of understanding the role of timbre in music was the composer and theorist Arnold Schoenberg in his now much-quoted statement found at the conclusion of his *Harmonielehre*:

> The evaluation of tone colour, the second dimension of tone, is in a much less cultivated, much less organised state than is the aesthetic evaluation of [pitch]. Nevertheless, we go

> right on boldly connecting sounds with one another, contrasting them with one another, simply by feeling; and it has never yet occurred to anyone to require of a theory that it should determine laws by which one may do that sort of thing... Now, if it is possible to create patterns out [of] pitch[es], patterns we call 'melodies,' progressions, whose coherence evokes an effect analogous to thought processes, then it must also be possible to make progressions out of ... 'tone colour,' progressions whose relations with one another work with a kind of logic entirely equivalent to that logic which satisfies us in the melody of pitches.[3]

Schoenberg never provided a theoretical basis for his 'tone colour progressions,' and it appears he wrote only one composition which overtly uses the idea — 'Farben', from *Five Pieces for Orchestra,* Op. 16 (1909). Other composers have, however, attempted to create a tone colour theory. Two musicians who represent two very different methods of tackling this problem are Wayne Slawson and Fred Lerdahl.

Wayne Slawson (1985) is a composer who has attempted to provide a systematic theory for composing with a sub-group of timbre, which he calls *sound colour.* Slawson proposes a two-dimensional sound-colour space, which he maps by the placement of different vowel sounds: the x axis represents the frequency of the first resonance, or formant, and the y axis represents the frequency of the second. Slawson defines certain types of movement within this sound-colour space during which a particular property remains invariant. He proposes that movement within the sound-colour space is open to the operations of transposition and inversion. His attempt to map timbre within a space with a small number of dimensions allies his work with that of the acousticians Grey (1975) and Wessel (1979). However, Slawson's theory is designed as a tool for composition, and because of its limited number of timbral possibilities, is not suitable as a tool for analysis.

The composer and theorist Fred Lerdahl (1987) proposes that timbre can be organised hierarchically based on the idea of timbral consonance and dissonance. He intuitively finds a 'brighter' sound more tense or dissonant than a 'dull' one (a violin is more dissonant than a viola), and a sharp attack or release more dissonant than a smooth attack or gradual release. He unifies the many possible timbral dimensions by the concept of timbral consonance and dissonance, and with the idea of a timbral 'scale' — 'a linear ordering of timbres at fixed intervals along a given dimension or combination of dimensions' that progress away from or towards the most consonant timbre. Lerdahl's theory accommodates the multidimensional aspect of timbre, and provides the basis for a timbre vocabulary. However, it is not sufficiently objective — the theory might perhaps work best as a personal compositional tool, rather than as an analytical method.

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[3] Schoenberg (1978): 421.

What must an analytical theory of timbre provide? In a review of Robert Erickson's *Sound Structure in Music* (1975) (which is a collection of interesting musical examples rather than the beginnings of a timbral theory), Richard Swift states his requirements for a method of timbre analysis:

> What is wanted is an account of tone quality that is not antagonistic toward other components of music or to other musical processes, but is congruent and coherent with them, an account which will strive to match, at the least, the level of recent intensive analyses of pitch, contour, harmony and structure.[4]

If a system for timbre analysis is to add to our understanding of musical structure, I believe that these criteria need to be met, and, using these criteria, both Slawson's and Lerdahl's theories fail as tools for timbre analysis.

At the beginning of this article, I wrote that the aural information that we call timbre consists of particular acoustic properties. An approach that does have the potential to live-up to Swift's analytical ideal is that taken by Robert Cogan, who analyses the sound spectrum of a performance of a composition. In his principal study involving spectrum analysis (1984), Cogan generates spectral measurements of entire pieces or sections of pieces by joining together photographs of the spectral display of a cathode ray tube — a method now superseded by computer technology, but at the forefront of technology at the time.

Cogan presents a theory for the analysis of spectrographs, leading to an understanding of what Cogan calls the *sonic design* of a piece. The theory, based on linguistic phonology, analyses sonic oppositions. By considering thirteen sonic oppositions (for example, grave/acute, narrow/wide, no-attack/attack, beatless/beating), Cogan assesses to what extent, for a defined segment of a piece, these attributes are present. Thus, for each oppositional pair, a segment of music may be classified as positive (+; a high energy state — e.g., acute), negative (–; a low energy state — e.g., grave), a mixture of positive and negative (±), or neutral (0). These classifications are judged within the musical context. By considering all the sonic oppositions in a section, Cogan can specify an overall timbral 'measure' for a section as well as specify ratios of change from section to section.

Richard Swift, whose review of *Sound Color* was quoted earlier, believes that 'Cogan has formulated a brilliantly viable theory of sound: a theory that ... [promises] to provide a basis for the analysis of sound.' However, Swift also points out that 'it might be objected that ... the adjectival characteristics of the terms in which the analysis is couched

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[4] Swift (1975): 158.

constitute banal binary oppositions, or that they are narrowly generalized… One views with some misgivings an analytical system that is so restrictive in its alternatives.'[5] Most importantly, in my view, Cogan treats the spectrum photos as direct representations of our perception — he does not attempt to interpret the spectral data in the light of perceptual models. He treats the spectra as objects in themselves, rather than as representations of data which can be manipulated further.

For successful timbre analysis, a spectrograph needs to be recognised as simply a representation of data — data that can be transformed in various ways, and data that contains much information that is not directly to do with our perception of timbre (that is, information on pitch, duration and overall loudness). Thus, there are two interlocking requirements for successful timbre analysis — the data needs to be weighted in order to accord more closely with models of auditory perception, and the mass of data that is represented by a spectrograph needs to be reduced so that we are left with information specifically to do with timbre. Once the information represented by a spectrograph has been weighted and reduced, we need methods for displaying and discussing this data that allows the richness and subtlety of timbre to be appreciated by allowing continuous movement between timbral categories. Lastly, the analysis of timbre needs to be integrated into a rigorous analysis of pitch and formal structures so that the interaction between various structural parameters of a piece can be clearly observed.

In order to achieve these aims, I have assembled a set of acoustic tools that extract particular perceptual timbral qualities. These tools are grounded in psychoacoustic research, and selected with the particular requirements of music analysis in mind. These tools help us to arrive at a plane of concepts and a vocabulary with which timbre can be rigorously discussed and analysed, rather than it being merely described, as has been the case in the past. In particular, this methodology allows the music analyst to begin to explore rigorously the timbral structures that are so important in 20th-century music, for example, in Ligeti's *Atmosphères* (1961). Indeed, the motivation for this research was my wish to understand this type of music more fully, to understand how a composer manages to create coherence and development through the actual 'sound' of the piece.

In order to introduce and describe the timbre analytical tools, let us begin with the work of the physicist and acoustician Harold Pollard (1988), who divides the task of the analysis of musical sound into three stages: physical analysis, psycho-physical analysis, and feature analysis. A spectrum analysis of a musical sound is a measure of some of the physical properties of that sound. If our understanding of the response of the human ear is applied to this data, we begin to move towards comprehension of our perception of this sound — a psycho-physical analysis. In order to move further towards perceptual understanding, we must attempt to discover the level of importance the brain assigns to different sorts of information, and how it groups this information — feature analysis. Feature analysis, arrived at through the weighting, reduction and grouping of the data from a physical analysis of a sound, is vital if we are to begin to close the gap between measurement and perception.

Pollard lists the following as important elements of Feature Analysis:

* assessment of the starting transient;
* sharpness (loudness centroid) as a function of time;
* timbre (a synthesis of factors, or equivalent measures as in the *Tristimulus Method* [discussed below]);
* pitch;
* loudness;
* fluctuations of loudness, pitch, and timbre;
* roughness (beats between partials in the same critical band);
* other cues (e.g., compactness, missing partials).

We can extract those elements from Pollard's list that are specifically to do with timbre — that is, those elements that are not to do with pitch, loudness or duration. Because of the focus in this study on the steady state element of sound, we can also exclude those elements that are to do with the way we perceive temporal change. This procedure leaves the following list of elements:

* timbre (as assessed by the Tristimulus Method);
* sharpness;
* roughness;
* other cues (e.g., compactness, missing partials).

(In this study, the Tristimulus Method is understood as a means of measuring an important aspect of our timbre perception, complementary to other measures (such as sharpness and roughness); it is not a measure of the entirety of our timbre perception, as is suggested by Pollard's wording.) By assembling a collection of tools that allows the above elements to be measured, we can collect data which allows the timbre of a piece to be described with precision.

These tools are summarised below:

* *Timbre*:

Pollard and Janson's Tristimulus Method (1982) has been shown to be a successful method for representing some of the information that is asso-

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[5] Swift (1986): 283.

ciated with our perception of timbre. The Tristimulus Method was designed specifically to analyse the timbre of a single tone — not the timbre of an ensemble sound, which is the more usual situation in Western music. In order to make it possible to move towards the analysis of the changing timbre of ensemble music, we have devised a new and original method in the spirit of the Tristimulus Method. This method is called *Loudness Distribution Analysis*. It produces three timbral measures — *timbral width, timbral weight*, and *timbral pitch*. Timbral width has proven to be the most useful of these timbral measures, and will be the only one of these three measures to be discussed here.[6]

* *Sharpness*:
There have been a number of psychoacoustic studies that have shown sharpness to be an important perceptual attribute (for example, Bismarck, 1974). In this study, sharpness is defined through the frequency position of the loudness centroid. (It is acknowledged that more complex methods exist for a measure of sharpness (see Goad, 1992), however the simpler method was chosen for this study.)

* *Roughness*:
Roughness is a perceptual term related to the musical term 'dissonance.' Roughness is caused through beating between partials. A method for calculating roughness has been proposed by Hutchinson and Knopoff (1978).

* Harmonicity and *other cues*:
A method for assessing the degree of *harmonicity* is *cepstrum analysis* — it shows to what extent a spectrum diverges from an 'ideal' harmonic spectrum (compactness), and to some extent will reflect the absence of partials. In comparison with the other proposed measures, however, cepstrum analysis appears to tell us less about a piece's timbre. Cepstrum analysis will not be discussed here (see Malloch, 1997, for examples of its use).

In the discussion of timbre analysis which follows, three complementary measures will be used — Timbral Width (one of the measures of Loudness Distribution Analysis), Sharpness and Roughness. Through the use of these analytical tools, a plane of concepts and a vocabulary for timbre analysis is established, and it becomes possible to analyse and understand a composer's use of timbre. Instead of music timbre analysis relying solely on vague descriptive terms, as it has so often in the past, these measures enable timbre analysis to be executed with the rigour we find in pitch analysis, and the interaction between structures of timbre, pitch and form can be, for the first time, investigated in depth.

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[6] For a discussion of the other measures, see Malloch (1997).

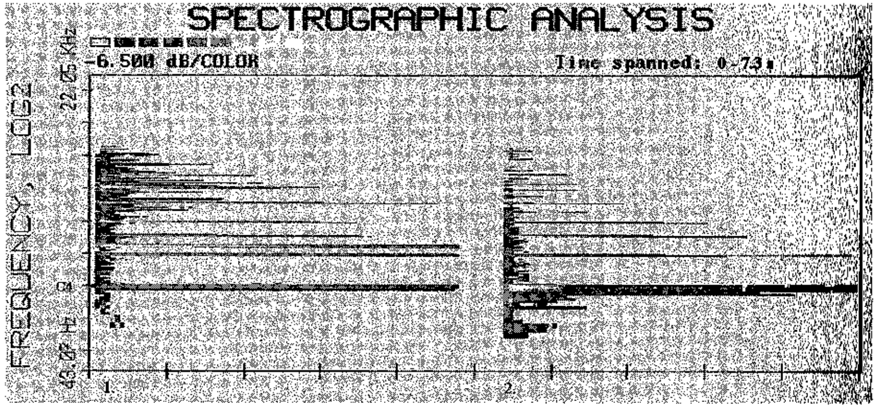

Figure 1 (1) Spectrum of carillon bell. (2) Spectrum of guitar tone

To begin the illustration of these techniques, let us examine how these methods can be applied to single sounds. Figure 1 shows the spectra of two contrasting timbres. The first is the spectrum of a Hemony carillon bell, with a strike note pitch around 500 Hz (hum note 251 Hz). The second is a guitar tone with a fundamental frequency of 251 Hz (a sharp B3). Frequency, on a logarithmic scale, is represented on the vertical axis of the graph, and the pitch C4 is shown as a point of reference (the marks on this axis above and below C4 are pitch-class C's at various octaves). Time is represented along the horizontal axis, and amplitude is shown by a grey scale, the calibration of which is given at the top-left of the graph. In this instance, there is a difference between each of the nine shades of grey of 6.5 dB. The greatest amplitude is assigned the colour white. An examination of the two spectra reveals that the second (guitar tone) is very largely composed of harmonic components, while the first (bell tone) contains many non-harmonic partials causing it to have less definite pitch.[7]

Spectrum analysis is useful for representing the 'acoustic outline' of a sound, or the 'sonic design' of a piece of music (as Cogan has shown). Some timbral information can be deduced from a spectrograph — the first sound of figure 1 is visually less 'pure' than the second. However, much more information on timbre can be shown if the data, as repre-

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[7] This spectrograph has been 'A-weighted' — that is, a simple mathematical formula has been applied to the intensity values of the spectral components in order that the relative intensities shown on the spectrograph are a better approximation of the effect of the components within the human ear. A-weighting weights all spectral components in a way roughly equivalent to the 40 phon equal loudness contour. Overall, the effect is that low and very high frequencies are attenuated, while the mid-range is boosted.

sented by a spectrograph, is weighted and reduced, and then the results displayed in a way congruent with our timbre perception.

It was stated above that Loudness Distribution Analysis is derived from Pollard and Janson's Tristimulus Method. The Tristimulus Method produces three values derived from the loudness distribution in the spectrum of a single pitched note. The total loudness (t) at a particular moment in the sound is divided into three frequency ranges: p_2 — the loudness of partials 5 and upwards; p_1 — the loudness of partials 2 to 4; and d the loudness of the fundamental:

$$t = p_2 + p_1 + d.$$

Values are then derived which convert these values to fractions of the total loudness:

$$x = p_2/t$$
$$y = p_1/t$$
$$z = d/t.$$

In the Tristimulus Method, loudness is grouped and measured from the fundamental upwards. In an ensemble sound, there is no single fundamental from which measurements can be based. However, in an ensemble sound our attention is likely to be drawn to the loudest element. Thus, in the Loudness Distribution Method, the loudest element is taken as the basis for the measurements. The value of the loudness of the fundamental in the Tristimulus Method is replaced with the value m — the loudness of the loudest 1/3 octave frequency band.[8] Two other variables can then be derived — n — the loudness of all frequencies above the loudest band, and o — the loudness of all frequencies below the loudest band. Thus, just as the total loudness (t) in the Tristimulus Method is the sum of the loudness of three sections of the spectrum (d, p_2, p_1), the total loudness (T) in the Loudness Distribution Method is the sum of m, n and o:

$$T = m + n + o.$$

Values for l, a and b may then be derived:

$$l = m/T$$
$$a = n/T$$
$$b = o/T.$$

l is the value of the relative loudness of the loudest band; a is the value of the relative loudness of all frequencies above the loudest band; b is the value of the relative loudness of all frequencies below the loudest band.[9]

The total fraction of loudness that lies outside of the loudest 1/3 octave band (the spread of the loudness) is calculated by a + b, which results in the measure called *timbral width* (which ranges from *focused* to *diffuse*). *a–b (timbral weight)*, and the frequency position of the loudest 1/3 octave band number (whose loudness is l — *timbral pitch*) can also be derived, though these measures are not discussed here (see Malloch, 1997).

Figure 2 is a graph of timbral width for the bell and guitar tones discussed above. Let us look first at the bell sound (the first sound represented on the graph). Timbral width ($a + b$) lies in the mid-range; it shows a steady decline during the first half of the sound (up to letter y), and minimum change during the second half. In other words, during the first half of the sound the timbre becomes more focused — a greater fraction of the total loudness lies within the loudest band than at the

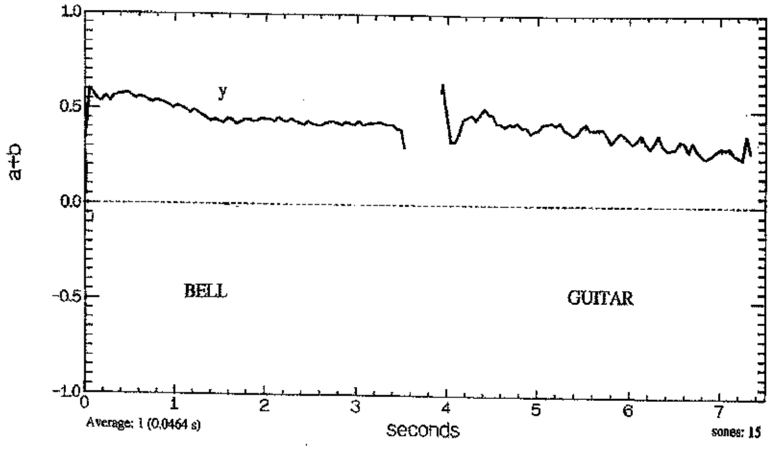

Figure 2 Timbral Width

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[8] Through psychoacoustic testing, it has been determined that the human ear divides the frequency spectrum into 1/3 octave bands — thus, this is a significant frequency band for psychoacoustic measures.

[9] As in the Tristimulus Method, loudness is calculated using Stevens' Mark VII Procedure (1972). This consists of calculating the loudness of all 1/3 octave bands in sones, taking into account frequency-weighting functions consisting of equal loudness contours, and applying a summation rule:

$$S_t = S_m + F(\Sigma S - S_m)$$

where S_t is the total loudness, S_m is the loudness of the loudest band, ΣS is the sum of the loudnesses of all the bands, and F is a factor that accounts for masking — F varies with S_m in a way defined by Stevens. Stevens' Mark VII Procedure was incorporated into a series of specially written computer programs for this study to calculate Loudness Distribution Graphs.

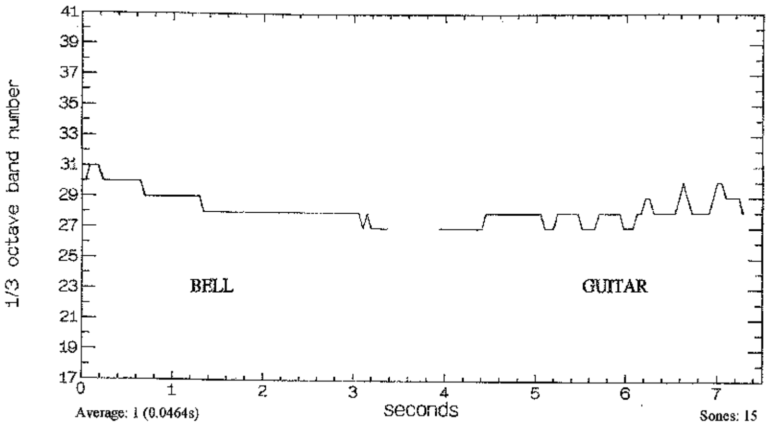

Figure 3 Sharpness

beginning. Similarly to the bell, the timbral width of the guitar tone shows a steady decline, the timbre gradually becoming more focused. The exception lies in the starting transient, where the timbre is initially more diffuse. If the reader imagines the sound of a guitar tone and a bell, it will be found that these graphs describe an important aspect of their timbre — how diffuse or focussed the sound is.

Moving to the measure of sharpness, in this study, sharpness measurement consists in locating the 1/3 octave band that corresponds with the loudness centroid (the centroid is the point on a graph where the areas below the graph, either side of the point, are equal in size). In Figure 3 we see a graph for the changing sharpness of the bell and guitar tones. The sharpness of the bell slowly falls (following the initial 'clang'), while that of the guitar rises as the sound dies away.

Roughness, or acoustic dissonance, is defined here as the beating that occurs between simultaneously sounding partials. As was stated above, roughness is not synonymous with musical dissonance — what is musically dissonant or consonant is defined through the practice of the era. Roughness is a perceptual measure inhabiting a world larger than that of musical practice.

The method for calculating roughness that is used here consists of a number of stages. Through psychoacoustic testing, Plomp and Levelt (1965) determined a curve that shows the degree of perceived dissonance of two simultaneously sounding sinusoids of equal amplitude as a function of critical bandwidth.[10]

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[10] A critical bandwidth is very similar to a 1/3 octave bandwidth.

Hutchinson and Knopoff (1978) have proposed a formula based on Plomp and Levelt's work for calculating the degree of beating between any number of sinusoids (and thus, between any number of complex tones). The roughness between *two* sinusoids may be calculated by:

$$R = \frac{A_1 A_2 g(f_1 - f_2)}{N}$$

where R is the roughness factor, A_1, A_2 are the acoustic amplitudes of the two sinusoids, and $g(f_1 - f_2)$ is a weighting factor (derived from the work of Plomp and Levelt) which is a function of the difference in the two sinusoidal frequencies f_1 and f_2. N is a normalising factor proportional to the total intensity:

$$N = A_1^2 + A_2^2.$$

The weighting factor, g, is calculated as:

$$g = |f_1 - f_2| / CBW(\bar{f})$$

where the critical bandwidth (CBW) is calculated as a function of the mean frequency of two simple tones:

$$CBW = 1.72(\bar{f})^{0.65}.$$

The formula for calculating R can then be modified for *complex tones* so that the numerator becomes the sum of all sinusoid-pair interactions within that complex tone, and the denominator the total power of the sound:

$$R = \frac{1/2 \sum_{i=1}^{N} \sum_{j=1}^{N} A_i Aj g_{ij}}{\sum_{i=1}^{N} A_i^2}.$$

As Hutchinson and Knopoff themselves say, this formula is not ideal, for it does not deal with the problem of phase shifts, nor does it address the problems associated with simply adding the roughness interactions of a sound that has very many components. However, the results reported by Hutchinson and Knopoff, as well as the results obtained during the work of this study, suggest that the formula is reliable when different sounds are compared.

Figure 4 shows a plot of roughness against time for the bell and guitar tones discussed earlier, calculated using a computer program that incorporates the formula described above.

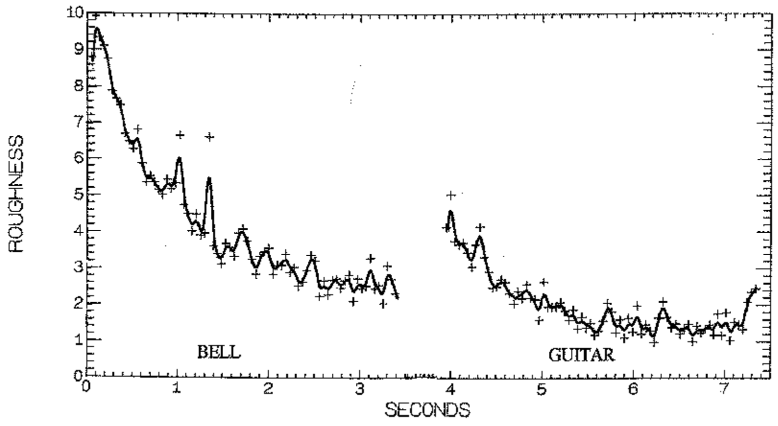

Figure 4 Roughness

The graph confirms expectations. We see that the bell tone shows about twice the roughness of the guitar tone if the beginnings of the sounds are compared. Fluctuations in the graphs are due to the varying relative strengths of the sounds' components over the length of the decay.

We now have the ability to measure and graph three very important aspects of our timbre perception, and we have seen how the analytical tools can be used for the description of the timbre of two contrasting sounds. Let us now combine these timbral measures in the analysis of a section of music. György Ligeti's *Atmosphères* (written in 1961) is scored for large symphony orchestra, and is constructed from shifting clouds of notes which expand and contract, and which move through constantly shifting timbres. The central point of the work consists of a very high-pitched note-cluster played by four piccolos (pitch-class set 4–1, G7 to B♭7) followed by a very low-pitched cluster played by eight double-basses (pitch-class set 8–1, C#1 to G#1). This is experienced as a very abrupt and dramatic change of timbre and pitch.

Figure 5 is a graph of timbral width for this section of the piece. The thicker line joins points 0.464 seconds apart. The thinner line joins points 0.0464 seconds apart. Thus, we can observe both detail structure, and larger-scale movement.[11] Letters on the graph enclosed in square brackets indicate the placement of the rehearsal letters in the score.[12]

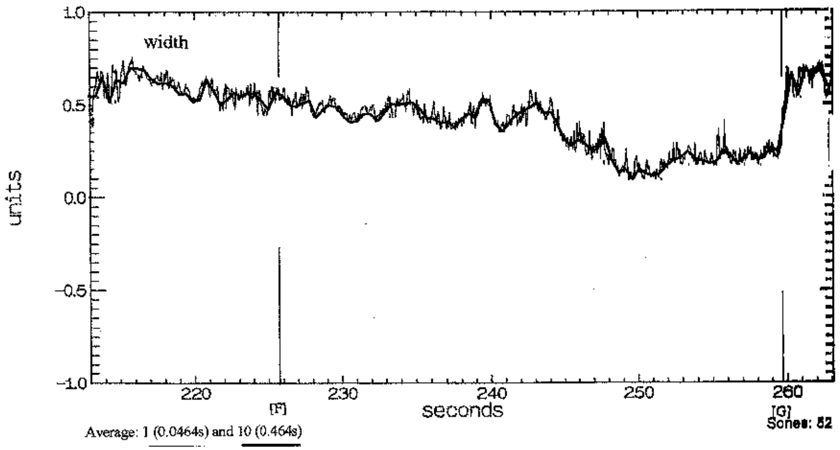

Figure 5 Timbral Width in *Atmosphères*

What does this graph describe? Up to the point on the graph before the 260th second, where the timbre suddenly becomes more diffuse, the piccolos, oboes, clarinets and trumpets have been playing, and becoming increasingly louder and higher in pitch. This has caused the timbre to become increasingly focused. At the 248th second, all wind instruments, but the piccolos, stop playing, while the piccolos continue to rise in pitch and increase in loudness. At the 250th second, the value for timbral width reaches its lowest point in this extract, showing that most of the loudness energy is now concentrated in the loudest 1/3 octave band. We hear a sound similar to a cluster of sine-waves. From this point to letter [G], timbral width becomes a little more diffuse. This reflects the effect of the piccolos increasing in loudness and 'forcing' the sound — the amount of 'noise' in the sound increases.

At letter [G], the double basses enter, playing forcefully and loudly, and there is a sudden rise in timbral width. Thus, these two very different timbres show very different measures of timbral width.

To the description of timbral width, we can now add descriptions of sharpness and roughness — other aspects of our timbre perception.

Figure 6 is a graph of sharpness for this same section of *Atmosphères*. As the instrumentation changes and as the pitch rises towards letter [G], sharpness increases. With the entry of the double basses, sharpness

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[11] The averaging process occurs at the very beginning of the calculation procedure, at the point loudness levels in 1/3 octave bands are calculated over a time interval that is a multiple of 0.0464 seconds (the smallest time-interval available within the limits of the software). In this instance, the averaging multiples are 1 and 10. From a perceptual viewpoint, it was considered better to average over the sound that we hear, rather than average over the results at the end of a complex series of calculations.

[12] The recording used for these measurements is the CD *Wien Modern*, Deutsche Grammophon 429 260–2 (1990): Wiener Philharmoniker, conducted by Claudio Abbado.

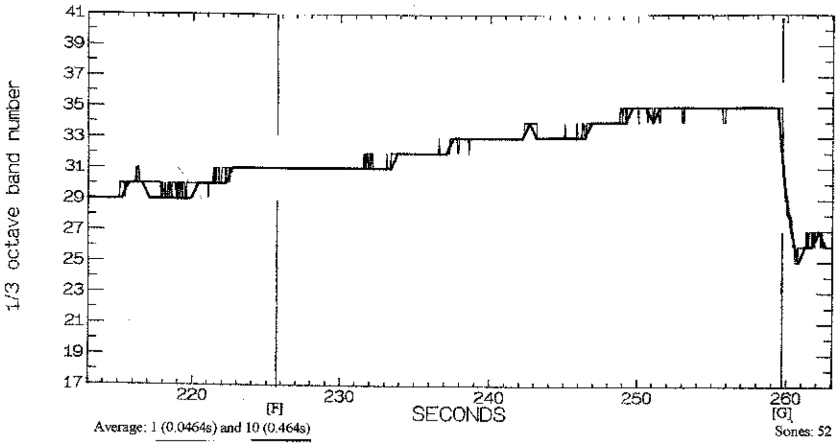

Figure 6 Sharpness in *Atmosphères*

suddenly drops, as would be expected. We can see that a measure of sharpness complements the information gained from the measure of timbral width.

Figure 7 shows a graph of roughness against time for the same section of music. As the wind instruments increase in loudness and tessitura, the degree of roughness increases, moving from a roughness measure of around 4 at letter [F], to around 8 half way through bar 36 (marked as x on the graph), where, overall, the instruments are playing at their loudest and highest. At the point aurally where the piccolos are left to play on their own (marked as y), there is a sudden drop in the roughness graph,

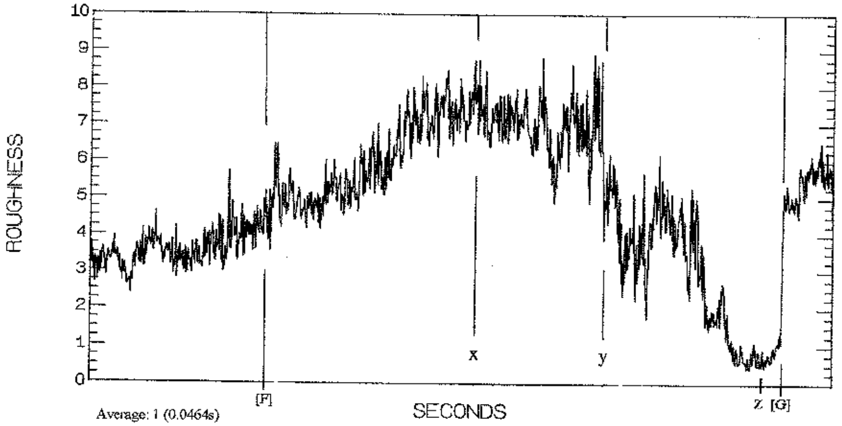

Figure 7 Roughness in *Atmosphères*

and the roughness measure continues to become lower as the piccolos continue to climb in pitch. This is due to fewer partials of the piccolo notes lying in such a way as to produce a significant level of roughness. Note the slight increase in roughness during bar 39 (z), where the piccolos all crescendo together to *fff*. This corresponds to the point of rising timbral width that was noted above. At the entry of the double-basses [G], there is a marked rise in roughness to a level equal to that heard at letter [F].

We can see that the measures of width, sharpness and roughness measure three different timbral attributes which all inform our overall perception of the changing timbre of the music. It is important to remember that it is our 'overall' timbre perception that these graphs are showing. The graphs cannot show how we perceive the piccolo timbre as a separate entity from the other woodwind timbres that occur at the same time, and the graphs cannot account for the way we can consciously focus-in on one timbre that is in the midst of many others. However, the graphs do show our overall timbre impression at any moment, and the overall timbre trajectory that the music takes.

The description of the movement of these measurable aspects of timbre constitutes the beginning of a timbre vocabulary. This timbre vocabulary allows for a detailed description of a particular timbre at a particular moment, and to view its development through the piece. With the existence of a precise timbre vocabulary, it becomes possible to undertake rigorous timbre analysis — we have already seen small-scale examples of this in the analysis of the bell and guitar tones, and in the analysis of a section from *Atmosphères*.

The aspects of timbre that have been chosen for analysis have been determined by the findings of previous acoustic and psychoacoustic studies (Sharpness, Roughness) and by the extrapolation from a pre-existing timbre analysis method (the Tristimulus Method, leading to a measure of Timbral Width). These timbre dimensions do not cover the entire scope of our timbre perception, but, from the evidence of the examples given in this article, it appears that these aspects of timbre do account for much that we perceive as timbre.

While changes in timbre are important in practically all musical compositions, it is in contemporary music that timbre at times becomes elevated to a structural importance equal to or superior to that of pitch structures. It is in this genre of music that timbre analysis techniques are especially needed — an analysis of pitch tells us only a part of the story (and often the less significant part) of how this type of music 'works'.

Now that a plane of concepts for timbre has been established, along with a precise vocabulary so that movement in timbre can be described, it now becomes possible to analyse timbre in a musical composition with as much depth and rigour as is possible in the pitch domain.

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