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Why is Musical Timbre so hard to understand?

Carol L Krumhansl

Abstract

Understanding musical timbre is a challenge to composers, music technologists, and perceptual psychologists alike. Various problems arise in the very definition of timbre; the complexity of acoustic measurements, the assumed independence of timbre from other dimensions of musical sound; and generalizing the notion of timbre beyond the set of traditional orchestral instruments. Perceptual studies have applied multi-dimensional scaling to discover dimensions underlying timbre differences. In addition to the common dimensions found (attack, brightness, and spectral flux), there may be dimensions or characteristics specific to each timbre. These cannot be accomodated in low-dimensional models. To test for the presence of specific dimensions, an extended multidimensional scaling model recently developed by Winsberg and Carroll[1] is applied to a set of timbre dissimilarity judgments made on the synthesized timbres described by Wessel, Bristow, and Settel[2]. The obtained common dimensions replicate earlier findings, but additional specific dimensions are obtained. Few studies have investigated the possibility of constructing timbre sequences with perceptable organizations. Analogies with pitch sequences may be limited owing to inherent differences between the two domains. Pitch is a homogeneous and uni-dimensional medium, whereas timbre is a multidimensional attribute. In addition, timbre has no natural equivalent of the octave or fifth, which are important in pitch structuring. Finally, qualities specific to individual timbres or regions of timbre spaces may limit the degree to which timbres can be hierarchically organized.

Introduction

Understanding timbre is perhaps the most challenging problem facing the musical community at the present time. For composers, especially those working in the electroacoustic medium, timbre seems to offer exciting new directions for musical invention. This is true to some extent for composers who employ traditional instruments in novel ways by changing how they are played or by modifying their action mechanically. For music technologists, the synthesis of timbre has proven to be a difficult problem. Whereas the control of the other dimensions of music, pitch, loudness, and duration, has not required special solutions, the control of timbre has. Music synthesis has raised crucial issues about how to produce rich and interesting-sounding timbres within the limits of available technology, and how to modify and transform them in compositionally useful ways. In music perception research, timbre is that aspect of music that is probably least well-understood. Psychoacoustics has provided detailed models of pitch and loudness perception, and there is a fairly large literature on the coding of temporal information. Recently, musical pitch and rhythm have stimulated a great deal of perceptual research taking a more cognitive orientation. Timbre is an area that is ripe for investigation, but certain methodological and conceptual problems arise.

The definition of timbre

The most basic problem is the definition of timbre itself. We are all familiar with the textbook definition: timbre is the way in which musical sounds differ once they have been equated for pitch, loudness, and duration. Although this is a logically tidy definition, it is at the same time not at all informative. It does not offer suggestions about what produces the residual differences we hear. To understand this, a necessary first step is to obtain acoustic measurements, most often taking the form of spectral energy distributions and amplitude envelopes. These descriptions, however, are so complex that it is difficult to isolate characteristics that distinguish between timbres. Moreover, the measurements do not provide information about which acoustic properties are, in fact, important for perception; only a very small subset of properties may have perceptual effects (see Risset and Wessel[3], for a more thorough discussion of these and related points).

A second problem with the textbook definition of timbre is the implicit assumption that timbre is independant of the other dimensions of musical sound. Can we really assume the differences in spectral energy distributions are completely uncoupled from pitch perception mechanisms in hearing? Can we assume that differences between amplitude envelopes are independent of duration judgements? Of course, we can design carefully controlled experiments in which we require listeners to adjust different timbres to be equal on these other dimensions. But, in my view, these tedious experiments, more than anything else, illustrate the artificiality of the definition. What seems to be a more fruitful kind of question is understanding how the various dimensions combine in perception, for example, how timbre interacts with pitch structure and temporal patterning to yield phrasing, rhythm, and a sense of musical form.

A third, and final problem with the textbook definition is that it is made with reference to traditional instruments. Timbre, the textbooks usually go on to say, is the way in which pianos differ from cellos, trombones from oboes, and so on, when they are all playing the same note for the same duration and at the same dynamic level. Within the domain of orchestral instruments, the definition may have a well-defined meaning, but it provide little guidance when it comes to considering the variety of sounds that can be produced with digital and anlog synthesis and with electronically modified live or recorded sounds, instrumental, vocal or other. Schaeffer[4,5] and Chion[6] have argued that once the domain is broadened in this way, the traditional definition of timbre becomes vacuous; they propose using the more general terms "sound object" or "sound material" instead. Even within the domain of orchestral instruments, an additional factor needs to be taken into account, which is how the instrument is being played. Is the violin bowed marcatto or legato; is the trumpet muted or not; is the flute played with a deep or shallow vibrato? The growing interest in expressive variations in musical performance highlights the problem of what level of description is most useful for describing timbres.

Thus, there are a number of problems with the textbook definition of timbre, but I doubt these will be solved by semantic arguments. Rather, musicians and scientists will adopt working definitions, depending on the focus of their compositional and experimental activities. However, before leaving the problem of definition entirely, I will add a few comments about the different levels of description that may apply to timbre. As I just indicated, one level of description takes into account the expressive variations available to performing musicians; this kind of microstructure may have parallels in electroacoustic music. At a somewhat coarser level of description, there are presumably commonalities shared by all oboe tones, all bowed violin tones, all timpani tones, and so on. These characteristics are of considerable interest for understanding the physics of musical instruments and synthesizing timbres to sound like traditional instruments, if that is the objective. At an even higher level, there may be even coarser classifications. One distinction at this level might be between instruments, such as percussive instruments, whose behavior is determined completely at the instant when they are set into motion, and instruments, such as blown and bowed instruments, whose behavior is controlled continuously.

This hierarchy of embedded distinctions, it seems to me, is quite different from another set of distinctions that sometimes arises in discussions of timbre (for example, Schaeffer[4,5], Chion[6], McAdams[7], Risset[8]). The latter has to do with varying degrees of temporal extent or musical complexity. Here, at the lowest level, are single, discrete sound events that are heard as being produced by a single source. At a somewhat higher level are emergent properties, such as texture, density, streams, and musical gestures. Finally, at an even higher level, there are larger-scale musical forms or organizations which grow out of the sound material. Distinctions between levels within these two hierarchies may not always be clear, but the two hierarchies seem quite distinct from one another.

The dimensions of timbre

With these preliminaries aside, I would like to turn now to issues concerning the perception of timbre. An approach that has been important in the perceptual literature has been to scale the perceived degree of relatedness between sounds with different timbres[9,10]. In concrete terms, what this means is that a set of sounds has been recorded in advance which vary in timbre but which do not vary in pitch, loudness, or duration. In the experiment itself, all possible pairs of timbres are presented to listeners, and for each pair they are required to rate how similar or dissimilar the two timbres are to each other. The resulting dissimilarity ratings are analyzed using a method called multi-dimensional scaling[11,12,13]. The multidimensional scaling algorithm applied to such data generates a geometric representation, usually in a low-dimensional space, such that similar timbres are associated with nearby points in the representation and dissmilar timbres are associated with distant points in the representation. In other words, perceived dissmilarities between timbres i and j are monotonically related to the Euclidean distance between points:

$$(\Sigma_k (x_{ik}-x_{jk})^2)^{1/2} \qquad (1),$$

where x_{ik} is the coordinate of the ith timbre on the kth dimension of the scaling solution, and Σ_k is the sum of the differences squared over the n dimensions of the solution. The interpretation of the spatial configuration is usually in terms of how the points line up with respect to the underlying dimensions of the space.

Wessel[9], using this method, obtained a two-dimensional solution. One dimension corresponded to the brightness of the steady state portion of the sound, with instruments whose energy concentrates in the high components separating from instruments whose energy concentrated in the low components. The second dimension showed an influence of both the rapidity of the attack and the relative onsets of high and low spectral components. Brass instruments (which have a rapid onset of low spectral components) separated from string instruments (which have more synchronous spectral evolutions). Grey's[10] study largely confirmed these results, but identified more clearly two separate dimensions having to do with temporal characteristics, one corresponding to rapidity of attack and the other to the synchrony of the amplitude changes in the spectral components.

I mention these well-known results for the purpose of suggesting one way in which perceptual experiments can lead to systematic descriptions of musical timbre. The approach, it should be emphasized, is completely general. Any kind of timbres, natural or artificial, can be presented in such an experiment, and the analysis of the data does not require that the nature, or even the number, of the underlying dimensions be known in advance. As such, it is a useful exploratory method. Note, moreover, that in these applications the extremely complex acoustic data are reduced to just a few underlying perceptual dimensions which are likely candidates for controlling in timbre synthesis. The success of the approach, however, depends on whether the dimensional model is appropriate from a psychological point of view. That is, the model can fit the data only if the timbres are perceived to differ along a few underlying dimensions. In these cases, the data are fit quite well by the model in a low-dimensional space, but there is a certain amount of variability in the data that is not accounted for by the model. Perhaps the simple dimensional model is not completely adequate.

Chion[5] has argued that timbre differences cannot be accounted for in objective, quantitative terms, unlike pitch, intensity, and duration which lend themselves naturally to such description. He compares the situation to differences between people, who can be characterized, say, in terms of their height, their weight and their age — quantifiable dimensions like pitch, intensity and duration. But, people also differ in unique physiognomic characteristics, such as facial features, which cannot be measured in a simple way. Perhaps timbres also have such unique, special characteristics and this accounts for some of the residual variability found in earlier scaling studies of timbre.

To investigate this possibility, David Wessel and I recently did a scaling study of a set of musical timbres, using the standard methodology described earlier. In this case, we used twenty-one timbres produced using the frequency modulation technique. Many of these timbres were designed to simulate traditional instruments, such as oboe, trombone, bowed string, harpsicord, and clarinet. A few others were hybrid timbres

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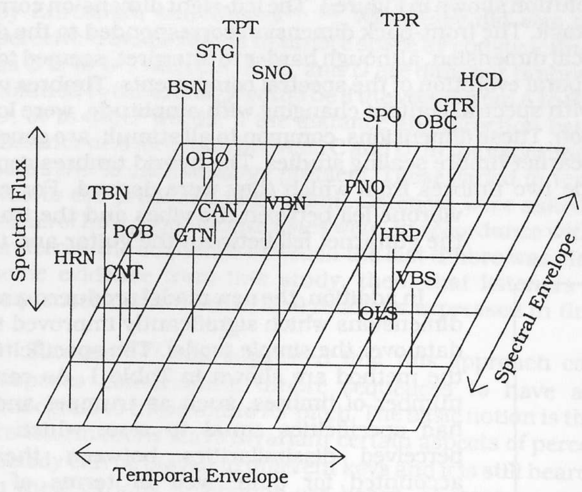

Figure 1. *Solution in the three common dimensions obtained using the common and specific dimensions model of Winsberg and Carroll[1].*

Abbrevation	Timbre	Specificity
HRN	Horn	7.90
TPT	Trumpet	0
TBN	Trombone	0
HRP	Harp	18.16
TPR	Trumpar (trumpet/guitar)	0
OLS	Oboleste (oboe/celeste)	0
VBS	Vibes	14.21
SNO	Striano (string/piano)	8.13
SPO	Sampled piano	0
HCD	Harpsichord	22.06
CAN	Cor anglais (tenor oboe)	9.37
OBO	Oboe	0
BSN	Bassoon	0
CNT	Clarinet	25.70
VBN	Vibrone (vibes/tormbone)	39.18
OBC	Obochord (oboe/ harpsichord)	0
POB	Pianobow (bowed piano)	22.14
GTR	Guitar	6.36
STG	String	7.10
PNO	Piano	13.81
GTN	Guitarnet (Guitar/Clarinet)	31.27

Table 1. *Specifties of Timbres.*

such as vibrone (a hybrid of vibres and trombone), guitarnet (a hybrid of guitar and clarinet), and trumpar (a hybrid of trumpet and guitar). More details of the construction of these timbres can be found in the paper by Wessel, Bristow, and Settel[2]. The listeners in our experiment were all musicians.

We conducted this experiment, in part, in order to test whether a new model of similarity scaling developed by Winsberg and Carroll[1] would reveal attributes specific to individual timbres, in addition to dimensions common to all timbres as has been found in previous studies. The essence of their model is as follows. Like traditional multidimensional scaling, their method finds a set of points in a lowdimensional coordinate space. However, each object under study, in this case, each timbre, is allowed to have a specific dimension of its own. These combine with the dimensional differences to produce an overall measure of dissimilarity. Specifically, perceived dissimilarity between timbre i and timbre j is monotonically related to:

$$(\Sigma_k (x_{ik}-x_{jk})^2+s_i+s_j)^{1/2} \quad (2),$$

where x_{ik} is the coordinate of the i^{th} timbre on the k^{th} dimension as before, as s_i is the measure of the specific dimension for timbre i.

When Suzanne Winsberg applied the technique to our scaling data, she obtained the three-dimensional solution shown in Figure 1. The left-right dimension corresponded to the rapidity of the attack. The front-back dimension corresponded to the dimension of brightness. The vertical dimension, although harder to interpret, seemed to correspond to aspects of the temporal evolution of the spectral components. Timbres with a brass-like characteristic, with spectral content changing with amplitude, were located at the top of the configuration. These dimensions, common to all stimuli, are generally similar to those obtained in earlier timbre scaling studies. The hybrid timbres generally fell at locations between the two timbres from which they were derived. For example, the vibrone fell between the vibes and the trombone, and the guitarnet fell between the guitar and the clarinet.

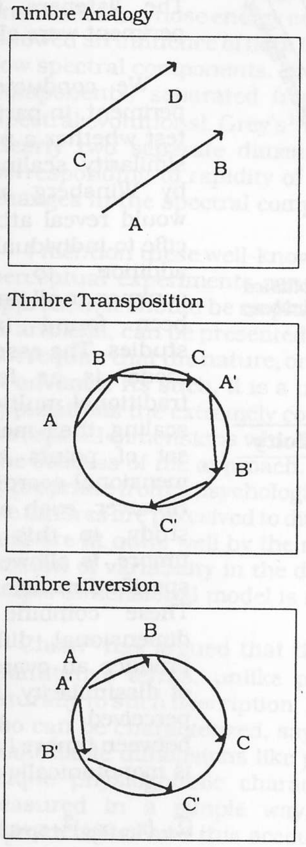

Figure 2. *Schematic illustration of timbre analogy (top panel), timbre transposition (middel panel), and timbre inversion (bottom panel).*

In addition, the new model produced a set of specific dimensions which significantly improved the fit to the data over the simple model. The specificities found by the method are shown in Table 1. As can be seen, a number of timbres, such as trumpet and trombone, had specificities equal to zero, which means, the perceived dissimilarities between them can be accounted for quite well in terms of the spatial distances. A number of other timbres, however, have large specificities, suggesting that they had unique properties that made them dissimilar from the other timbres. For example, the offset of the harpsicord is distinctive, and the clarinet is unique in its absence of even harmonics; these have relatively large specificities. The interpretation of these specificities is, at this point, intuitive and needs to be substantiated by acoustic analyses and further perceptual tests. However, these preliminary findings do suggest that timbres may well have unique characteristics, although there remain a few common dimensions in terms of which all timbres differ.

Perceiving timbral organizations

The scaling studies described in the last section suggest that, at least for the kinds of instrumental timbres employed, listeners perceive different timbres as more or less related. These relations can be summarized, in part, in terms of spatial representations, sometimes called timbre spaces. Can this kind of information be used to suggest ways in which sequences of timbres might be organized in music? Is there any evidence that the structural relations expressed in these representations have consequences for the way listeners perceive longer sequences of timbres?

To my knowledge, the only experimental study addressing this latter point was done by Ehresman and Wessel[14, 15]. What they did was to test whether it is possible to perceive transpositions in timbre space by constructing analogies of the form " A is to B as C is to D", where A, B, C, and D are different timbres. As shown in Figure 2, a good solution to the analogy would be if the vector from A to B was equal to the vector from C to D, or in other words, if the distance and direction between A and B was equal to the distance and direction between C and D. In the experiment, listeners heard four possible solutions to each analogy problem. These varied in terms of how close the last timbre was to the predicted ideal point. Listeners were asked to rank the four sequences in terms of how good the analogies were. In accordance with the predictions, they generally preferred the sequence in which the last timbre was closest to the ideal point. There is some evidence from this study, then, that listeners can perceive in longer timbre sequences certain structural relations expressed in timbre spaces.

Slawson[16,17] has suggested that this approach can be taken much farther. He proposes constructing timbre sequences to have a variety of formal properties analogous to those found for pitch. The basic notion is that, at least for pitch, a variety of transformations leave invariant certain aspects of perceived structure. For example, a melody can be played in different keys and it is still heard as the same melody[18]. Chords in their various inversions are heard, at least by experienced musicians, as being similar[19]. And there is some evidence[20,21,22] that listeners perceive invariances in pitch sequences despite mirror transformations (retrograde, inversion, and retrograde inversion).

The question of whether analogous invariants can be perceived for timbre sequences is an intriguing one, inviting experimental analysis. However, there may be inherent differences between pitch and timbre that will turn out to restrict the degree to which analogies will hold across the two domains.

Pitch structures are built from what is essentially a homogenous medium. That is to say, there is no essential way in which one pitch differs from another except along the continuous dimensions of pitch frequency. In contrast, timbres may have multiple characteristics in terms of which they differ. As was mentioned earlier, timbres may be distinguished by properties specific to each, such as distinctive offset characteristics or unique patterns in the harmonic spectra. In addition, the evidence suggests that timbre is a multidimensional attribute. It may be that a change along one dimension of the space is qualititatively different from a change along another dimension of the space. For example, a change in brightness may not be perceived as equivalent to a change in rapidity of attack, even if the timbre pairs are chosen to be equally dissimilar. In this connection, it is important to note that in Ehresman and Wessel's[14,15] analogies, the timbre pairs were equated not only for distance in the space but also for direction. I suspect this is essentional to their result.

Slawson's[16,17] transformations, in contrast, do not necessarily preserve directional distances; in fact, in most cases they do not. Figure 2 shows two of the proposed transformations, transposition and inversion. As can be seen, these transformations result in patterns shifted in the space without regard for the underlying dimensions. It may be that the kinds of timbres which he is using, generealizations of vowel sounds, are inherently more homogenous than the kinds of instrumental timbres used in the scaling invariant structures under transformations. However, it should be remembered that linguistic analyses of vowel sounds (for example, in Fant[23]) have found it useful to employ distinctive features, such as spread, flat, tense, and sharp. Thus, even vowel and vowel-like sounds may differ in important ways in terms of numerous underlying features or dimensions.

One might give the counterargument that pitch, too, is multidimensional. Shepard[24], for example, proposed a five-dimensional solution. Two dimensions accomodate the chroma circle on which octave equivalent tones are identified; two other dimensions accomodate the circle of fifths, and the final dimension corresponds to pitch height. There are two points to be made in this connection. The first is that, despite the high dimensionality of the representation, the space is considered isotropic; that is, intervals of the same size are considered equivalent no matter the direction of the vector between them. The second point is that the special nature of octaves and fifths, on which this kind of pitch model is based, probably is a consequence of the harmonic structure of complex tones. Specifically, the octave and the fifth appear early in the harmonic sequence. Thus, special relationships between tones in these intervals may derive naturally from the sounds themselves. No equivalent appears for timbres, as Slawson[16,17] has also noted.

This leads to the next point concerning analogies between pitch and timbre. In my own work on pitch structures, I have emphasized the psychological importance of tonal and harmonic hierarchies in traditional Western music[25,26,27]. Pitch hierarchies also seem to be perceived in music based on North Indian scales[28], octatonic scales[29], and tone rows[22]. Indeed, it seems to be hard to talk about any aspect of music without referring to some notion of hierarchy. For example, it plays a central role in coding theories of pitch sequences[30], in formal treatments of rhythm and meter [31,32], and in the analysis of longer time-spans[33].

Is the notion of hierarchy applicable to timbre also? Lerdahl[34] has recently argued that it is, and has suggested extending the prolongational reduction formalisms of Lerdahl and Jackendoff's[33] theory from pitch to timbre. At the center of Lerdahl's proposal is the idea that timbres inherently differ in terms of a quality he calls timbral "dissonance". Timbres that are bright, have sharp attacks, or have inharmonic spectra, he suggests, are more "dissonant" than timbres with the opposite properties. This may lead to a feeling of tension and relaxation when moving from "dissonant" timbres to "consonant" timbres. If there are perceptual effects of this kind, hierarchies may not be able to be imposed arbitrarily on timbres, but may need to originate in the qualities of the sounds themselves. In contrast, pitch hierarchies are essentially relational, established by the particular musical context. One promising direction, it seems to me, is to explore the potential for hierarchial structuring of timbres beginning with their inherent differences. These explorations may suggest ways of constructing timbre sequences with perceptable organizations. These may or may not turn out to have formal properties in common with other aspects of musical structure.

I will close by mentioning a list of miscellaneous issues, some of which are raised by possible analogies between pitch and timbre organizations. The first is the potential of context for altering perceived timbre intervals. Musical pitch studies have found tonal context significantly alters the perceived similarities between tones[35] and between chords[27]. Whether or not timbre intervals are similarly context-dependent is an empirical issue, but the influence of consonantal context on vowels in speech suggest that at least vowel-like timbres might be influenced by context.

A second issue is whether timbres are perceived categorically, or whether it is possible to effect perceptually continuous transformations in timbre space. The categorical nature of pitch interval judgments has been documented, for example, by Burns and Ward[36], see their paper, however, for variuos qualifications), and Grey[37] found discontinuities in the identification of timbres varying along a continuum. If categorical boundaries do, indeed, exist in timbre space, this may interfere with the perception of invariances under transformation.

A third issue concerns differences between simultaneous and successive combinations. Theoretical and empirical analyses of pitch have found it useful to distinguish between melodic and harmonic processes. Similarly, the effects of simultaneous combinations of timbres might be quite different from successive combinations. McAdams[38] demonstrated amplitude and frequency modulation are powerful factors governing fusion of simultaneous combinations, whereas very different principles may govern successive combinations.

The final issue is the relative importance of the different dimensions of musical sound. Can timbre be used only to highlight other aspects of musical structure, such as melody and rhythm? Or should it be considered to have an organization function in its own right? Van Noorden[39] and Wessel[15] have shown timbral differences can produce stream segregation, suggesting that timbre has strong organizational effects independent of other dimensions of musical sound. The potential for timbre to influence perceived musical structure on a larger scale has, to my knowledge, not been evaluated.

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