Perspectives in Systematic Musicology

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Auditory Roughness as a Means of Musical Expression

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This study argues that auditory roughness (rattling sound associated with certain types of signals) is an important sonic aspect of music, one that musical aesthetic judgments around the world are often based on. Within the Western tradition there is a strong link between roughness and annoyance, manifested in the assumption that rough sounds are inherently bad or unpleasant and are therefore to be avoided. Instrument construction and performance practices outside the Western art musical tradition, however, indicate that the sensation of roughness can be an important factor in the production of musical sound. Manipulating the roughness parameters helps create a buzzing or rattling sonic canvas that becomes the backdrop for further musical elaboration. It permits the creation of timbral or even rhythmic variations (through changes among roughness degrees), contributing to a musical tradition's menu of expressive tools. The potential usefulness of a proposed roughness estimation model to musicological research is discussed, drawing on previous and new empirical studies that link dissonance and roughness ratings of harmonic intervals within the Western chromatic scale. It is argued that, within the Western musical tradition, clear presence or absence of roughness dominates dissonance ratings. In most other cases, decisions on dissonance seem to ignore roughness and be culturally and historically mediated.

1. Introduction

Years of ethnomusicological research have shown that aesthetic judgments on pieces of music are culture dependent, with no fixed, cross-culturally accepted aesthetic criteria. At the same time, such judgments are not arbitrarily imposed on pieces of music by musical traditions, and aesthetic criteria are not, in general, invented out of thin air. Rather, they are based on how each different tradition chooses to interpret and value contextual, functional, performance, formal, and (more importantly for the present study) sonic aspects of musical pieces, with aesthetic differentiation going hand in hand with, if not preceding, aesthetic judgment. Interpretive choices and value judgments, which are at the center of all musical experience, have both cognitive and cultural bases and, like all choices, are essentially historical in their reliance on past experiences and in their power to configure future ones. History is understood here in the Gadamerian sense (Gadamer 1989: 265–300), while the notions of past, present, and future are informed by Ricoeur's (1984: 52–87) theory of mimesis. The present study argues that auditory roughness is an important sonic aspect of music, an aspect that aesthetic judgments are often based on.[1] The study examines ways in which roughness provides means of aesthetic differentiation, and how it is utilized and judged within different musical traditions.[2]

The term *roughness* describes an aural sensation and was introduced in the acoustics and psychoacoustics literature by Helmholtz (end of the nineteenth century) to label harsh, raspy, hoarse sounds. It refers to a harshness perceived when sound signals with an amplitude fluctuation rate between ~20 and ~75–150 fluctuations per second (depending on pitch register) reach the ear. Figure 1a shows an example of a signal with steady amplitude over time, while Figure 1b shows a signal whose amplitude fluctuates over time.

If the rate of fluctuation is within the previously mentioned range, the signal will correspond to a rough sound. A familiar example of a signal corresponding to a rough sound would be the signal of a harmonic minor second performed, for instance, on two flutes. Although a harmonic minor second will sound rough regardless of the sound sources involved, steady state sources such as singing voice, bowed strings, and winds (as opposed to impulse sources such as percussion and plucked strings) result in more salient roughness sensations (von Bèckèsy 1960; Terhardt 1974). At relatively low registers, wider intervals such as major seconds and minor thirds can also sound rough and, within the Western musical tradition, are avoided as dissonant. For example, the general practice in Western art music orchestration of spacing out harmonic intervals more at low registers than at high registers has its basis on roughness considerations.

The reason signals of all harmonic intervals other than unisons exhibit amplitude fluctuations is physical and is related to the phenomenon of interference. The reason why the signals of some of these intervals correspond to rough sounds is physiological and has to do mainly with the mechanical properties of the inner ear. The following section examines briefly the above issues by addressing the physical, physiological, and

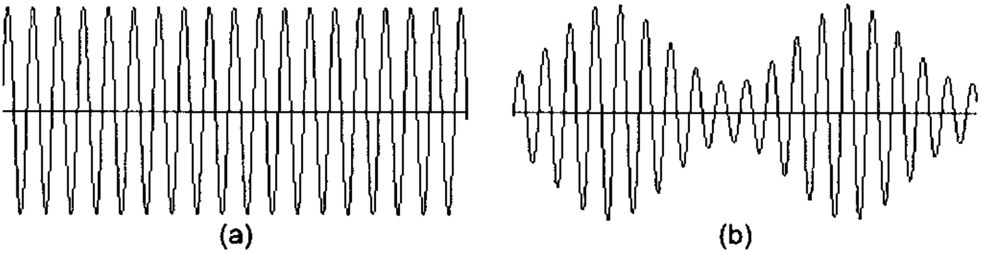

Figure 1. Illustration of a sound signal with (a) steady amplitude and (b) amplitude that fluctuates over time.

perceptual properties of signals with amplitude fluctuations (also often referred to as "modulated signals").

2. Physical and Physiological Correlates of the Roughness Sensation

The present study approaches roughness as one of the perceptual manifestations of the energy content of amplitude fluctuation and one aspect of timbre. Amplitude fluctuations describe variations in the maximum value (amplitude) of sound signals relative to a reference point and are the result of wave interference. The interference principle states that the combined amplitude of two or more vibrations (waves) at any given time may be larger (constructive interference) or smaller (destructive interference) than the amplitude of the individual vibrations (waves), depending on their phase relationship. In the case of two or more waves with different frequencies, their periodically changing phase relationship results in periodic alterations between constructive and destructive interference, giving rise to the phenomenon of amplitude fluctuations.

Amplitude fluctuations can be placed in three overlapping perceptual categories related to the rate of fluctuation. Slow amplitude fluctuations (≈≤20 per second) are perceived as loudness fluctuations referred to as beating. As the rate of fluctuation is increased, the loudness appears to be constant and the fluctuations are perceived as "fluttering" or *roughness*. As the amplitude fluctuation rate is increased further, the roughness reaches a maximum strength and then gradually diminishes until it disappears (≈≥75–150 fluctuations per second, depending on the frequency of the interfering tones).

Assuming the ear performs a frequency analysis on incoming signals, as indicated by Ohm's acoustical law (see Helmholtz 1885; Plomp 1964), the above perceptual categories can be related directly to the bandwidth of the hypothetical analysis-filters (Zwicker *et al.* 1957; Zwicker 1961). For example, in the simplest case of amplitude fluctuations resulting from the addition of two sine signals with frequencies f_1 and f_2, the fluctuation rate is equal to the frequency difference between the two sines $|f_1\text{-}f_2|$, and the following statements represent the general consensus:[3]

a) If the fluctuation rate is smaller than the filter-bandwidth, then a single tone is perceived either with fluctuating loudness (beating) or with roughness.
b) If the fluctuation rate is larger than the filter-bandwidth, then a complex tone is perceived, to which one or more pitches can be assigned but which, in general, exhibits no beating or roughness.[4]

Along with amplitude fluctuation rate, the second most important signal parameter related to roughness is the degree of a signal's amplitude fluctuation, that is, the level difference between peaks and valleys in a signal such as the one in Figure 1b (Terhardt 1974; Vassilakis 2001: Chapter 3). The degree of amplitude fluctuation depends on the relative amplitudes of the components in the signal's spectrum, with interfering tones of equal amplitudes resulting in the highest fluctuation degree and therefore in the highest roughness degree.

For fluctuation rates comparable to the auditory filter-bandwidth, the degree, rate, and shape of a complex signal's amplitude fluctuations are variables that, as it will be shown, are manipulated by musicians of various cultures to exploit the beating and roughness sensations, making amplitude fluctuation a significant expressive tool in the production of musical sound.[5] Otherwise, when there is no pronounced beating or roughness, the degree, rate, and shape of a complex signal's amplitude fluctuations are variables that continue to be important through their interaction with the signal's spectral components. This interaction is manifested perceptually in terms of pitch or timbre variations, linked to the introduction of combination tones.[6]

Similarly to beating, the roughness sensation associated with certain complex signals is therefore usually understood in terms of sine-component interaction within the same frequency band of the hypothesized auditory filter, called *critical band*. The term *critical band*, introduced by Fletcher in the 1940s, referred to the frequency bandwidth of the then-loosely-defined auditory filter. Since von Békésy's studies (1960), the term also refers literally to the specific area on the basilar membrane (an elongated thin sheet of fibers located in the inner ear, inside the cochlea) that goes into vibration in resonance to an incoming sine wave. Its length depends on the elastic properties of the membrane and on active feedback mechanisms operating within the hearing organ. Converging psychophysical and psychophysiological experiments indicate that the average length of the critical band is ~1mm. Psycho-physiologically, the roughness sensation can thus be linked to the inability of the auditory frequency-analysis mechanism to resolve inputs whose frequency difference is smaller than the critical bandwidth and to the resulting instability or periodic "tickling" (Campbell and Greated 1987:61) of the mechanical system (basilar membrane) that resonates in response to such inputs.

3. Western Musical Aesthetics and Roughness

Within the Western musical tradition, auditory roughness has often been linked to the concepts of consonance and dissonance, whether those have been understood as aesthetically loaded, as is most often the case, (Rameau in Carlton 1990, Kameoka and Kuriyagawa 1969a, Terhardt 1984, and others) or not (Helmholtz 1885, Hindemith 1945, von Békésy 1960, Plomp and Levelt 1965, and others). Studies addressing this sensation have occasionally been too keen to establish a definite and universally acceptable justification of the "natural inevitability" and "aesthetic superiority" of Western music theory (for example, Stumpf 1890, in von Békésy 1960: 348; Vogel 1993). This has prevented them from seriously examining the physical and physiological correlates of roughness, an important but certainly not the only perceptual dimension of dissonance. On the contrary, Helmholtz (1885: 234–235), the first researcher to examine roughness theoretically and experimentally as an important attribute of auditory sensation, concluded:

> Whether one combination [*of tones*] is rougher or smoother than another depends solely on the anatomical structure of the ear, and has nothing to do with psychological motives. But what degree of roughness a hearer is inclined to . . . as a means of musical expression depends on taste and habit; hence the boundary between consonances and dissonances has frequently changed . . . and will still further change.

Other researchers (for example, Ortmann 1922), as early as the beginning of the twentieth century, have gone even further to suggest that the most important factor in the enjoyment of music is nonauditory, with roughness being much less important than the listener's associations when it comes to music evaluation and appreciation.

After Helmholtz's work, the roughness sensation got little attention in psychoacoustics until the 1960s when studies by von Békésy, Terhardt, Plomp, and others acknowledged roughness as one of the main attributes of timbre.[7] Since then, further studies have demonstrated that this sensation plays an important role in several aspects of sound evaluation, both musical and nonmusical. Within several traditions, the consonance or "absence of annoyance" in nonmusical sounds has also been shown to depend on roughness. For example, studies indicate that listeners judge background noise that is rough as more annoying than "smooth" background noise (for example, Vos and Smoorenburg 1985, Hashimoto and Hatano 1994). (See Imaizumi 1986 for applications of roughness evaluation in voice pathology). More relevantly to the present study, Pressnitzer *et al.* (2000) confirmed that, as the perceptual salience of other sonic attributes such as pitch and tonal character is reduced, the correlation between nontonal tension and roughness increases.

This strong link between roughness and annoyance within the Western musical tradition has resulted in avoiding sound-combinations that sound rough (other than to signify that something horrible is going on) and has been accompanied by the unjustified assumption that rough sounds are inherently bad and unpleasant.[8] The present study treats the sensation of roughness as a perceptual manifestation of the energy content of amplitude fluctuation, which can be manipulated by controlling the fluctuation rate and degree to provide means of sonic variation and musical expression. As the following section will demonstrate, sound variations involving the roughness sensation often constitute a significant and valued expressive tool in the production of musical sound around the world, having both sonic and cultural significance.

4. Roughness as a Means of Musical Expression

4.1 Introduction

The sensation of roughness has been exploited more than any other perceptual manifestations of amplitude fluctuation and by numerous musical traditions, a practice that has not yet been well documented or researched. Manipulating the degree and rate of amplitude fluctuation helps create the buzzing sound of the Indian *tambura* drone and the rattling effect of Bosnian *ganga* singing, resulting in a sonic canvas that becomes the backdrop for further musical elaboration. It permits the creation of timbral variations (as, for example, in Middle Eastern *mijwiz* playing) and rhythmic contrasts (as, for example, in *ganga* singing) through gradual or abrupt changes among roughness degrees. Whether such variations are explicitly sought after, as in *ganga* singing and *mijwiz* playing, or are introduced more subtly and gradually, as may be the case in the typical chord progressions/modulations of Western music, they form an important part of a musical tradition's expressive vocabulary.

Important clues regarding the ways a musical culture approaches the roughness sensation can be identified through an examination of musical instrument construction, performance practice, and the different choices among musical traditions with regards to vertical sonorities such as harmonic intervals and chords. The following sections provide three examples of musical traditions that utilize the expressive possibilities of the roughness sensation. Other similar examples can be found in Quechua Haraui songs of Peru, with their frequent use of narrow harmonic intervals, and in the performance of the *taqara* flutes of the Xingu river in Brazil, where sonic effects similar to those produced with the *mizwij* are produced by two or more simultaneous performers.

4.2 The Middle Eastern Mijwiz

The *mijwiz* is an aerophone made out of two identical cylindrical cane pipes, each with a single reed, bound together and played simultaneously (Figure 2). Paired reed-pipes are found all across the Mediterranean. Their considerable cross-cultural and historical consistency with regards to playing technique, musical style, and even musical symbolism has often been attributed to their peculiar acoustical properties (Racy 1994: 38).

The *mijwiz* has a stepped shape. Each of the two pipes is made by joining together three cane tubes of increasing diameter: one that has the vibrating reed, one that acts as a junction, and one that carries the tone-holes. This construction gives the instrument acoustical characteristics that resemble those of conical rather than cylindrical

Figure 2. Ali Jihad Racy (University of California, Los Angeles, Ethnomusicology Department) performing on the *mijwiz*. Circular breathing is a technique used often by accomplished performers to ensure uninterrupted sound with no dynamic variation.

tubes, regarding register (an octave higher than a cylinder of the same dimensions) and spectral composition (denser, richer spectra) of the produced tones. Additionally, the discontinuities of the *mijwiz's* stepped design support a complex mode distribution that results in slightly inharmonic spectral components, as is the case with all compound horns (Fletcher and Rossing 1998: 217). The stepped design helps the instrument speak better because it allows for the use of a smaller reed system, as Racy has noted (1994: 42), but also because it provides better impedance matching between the inside and the outside of the instrument than a cylindrical tube (Nederveen 1998: 59–60). Nonetheless, since the effective cone-angle is very small, as is the diameter of the bore and of the tone holes, the resulting impedance matching is still weak. As a consequence, a large amount of pressure is required before the necessary standing waves can build up inside the tube and transfer energy outside the instrument, a pressure that must stay relatively constant if it is to sustain the free-reed vibrations and a steady tone.

The constant high pressure results not only in a constantly *nasal* tone, rich in upper components, but also in an extremely limited dynamic range. In addition, the equally narrow melodic range (~a fifth), the fact that the two reeds are activated just by air pressure (with no manipulation possible from the lips or tongue, as would be the case for a clarinet-like instrument, where reed manipulation by the lips/tongue permits timbral variation), and the frequent use of the circular-breathing playing technique (which further limits the possibilities for sonic variation by inhibiting any interplay between sound and silence), result in an instrument that has developed a celebrated expressive power without relying on any of the usual sonic expressive tools.[9] For its expressive power, the *mijwiz*, like most double-pipes throughout history, relies mainly on the manipulation and exploration of amplitude fluctuation rates.

The slight detuning between the two, otherwise identical, cane pipes (achieved through slight displacement of the tone-holes) means that when played together, they produce tones that beat constantly and at slightly shifting rates, giving the instrument a rich tonal quality. The shifting beating rates are owed to the slight inharmonicity of the upper components (due to the stepped design), and may be behind the "chorus effect" noted by Racy (1994: 44). The amplitude fluctuation rate is explored further by occasionally increasing the detuning of the near-unisons through partial stopping or by temporarily abandoning the unisons and using one pipe as a high drone while performing a lower melody on the other. With a functional range of approximately a fifth and no possibility of line crossing, this motion between unison, detuned unison, and minor second to minor third harmonic intervals represents a manipulation of roughness degrees rather than a form of polyphony. In its construction and performance practice, the *mijwiz* is an example of an instrument that makes explicit use of the perceptual richness of amplitude fluctuation, through creative exploration of the roughness sensation.

4.3 *The North Indian* Tambura

The structural and symbolic importance of the interaction between drone and melody, exemplified by the role of the *tambura* in Indian musical ensembles, is indicative of the musical significance of sonic contrasts involving the roughness sensation. The *tambura* is an unfretted, long-necked lute with four or five strings (tuned to octaves and a fifth, a fourth, or a seventh, depending on tuning set), used to provide the drone accompaniment for one or more melodic instruments (Figure 3). A cotton thread (*juari*, often referred to as "life giving thread") is inserted between the bridge and the strings, giving the modulation of the string-length (as the string wraps/unwraps around the bridge) a discontinuous character and resulting in the characteristic, buzzing sound of the instrument. The buzzing is accentuated by the fact that high-frequency waves (associated with the abrupt changes in string slope and the "whipping" of the bridge) propagate on the string faster than lower-frequency waves (dispersion due to string stiffness), reinforcing the energy shift to upper components and increasing the "brilliance" of the buzz.

The buzzing sound of the *tambura* strings provides a dynamic drone of up to four tones that interact with each other and with the melodic line they support. This interaction between background (drone) and foreground (melodic line) results in roughness variations that outline the function of each note within a *rãg* (scale) and provide a point of reference for measuring the relationships among the intervals used. These relationships are responsible for the dynamic quality of a note within a melody, describing a note's degree of instability/tension. They set up patterns of tension and release within a piece of music, governed by the degree of roughness experienced in relation to the first *tambura* drone, and complicated further by the introduction of a second or third drone (Jairazbhoy 1995: 65–69).

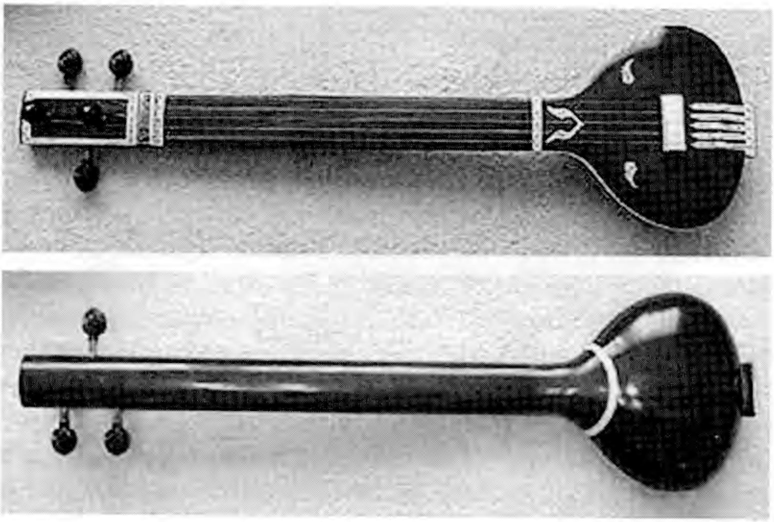

Figure 3. The front and back of a five-string North Indian *tambura*. (From the Ethnomusicology Department's instrument collection, University of California, Los Angeles.)

Contemporary North Indian classical music theory links sound to emotion (*rasa*), color, the Hindu deities, and more. The concept of rāg is partly based on the idea that certain note-patterns evoke a heightened state of emotion (Jairazbhoy 1995: 28). It has its roots in the second half of the seventeenth century and is a direct descendent of the ancient court tradition, where the patronage system created a highly competitive atmosphere (Jairazbhoy 1995: 21, 27). Virtuosity, invention, and showmanship have therefore always played an important role, with the sonic effect of a musical performance holding special significance. This effect is mainly based on contrasts between states of tension and release or, as Jairazbhoy puts it (1995: 70), on contrasts of energy levels. The roughness sensation is at the root of these energy-level contrasts, with the *tambura's* buzzing sound often considered the life of a musical piece (Carterette *et al.* 1989: 87).

4.4 Bosnian **Ganga** *Songs*

Ganga is a style of singing common in Bosnia-Herzegovina and the Dalmatian Zagora regions of the Balkans. *Ganga* songs consist of two alternating sections, one sung by a soloist and one by a soloist and a chorus (three to five singers). The melodic range rarely exceeds a fourth while, in the choral sections, voices sing at minor/major second harmonic intervals that may or may not alternate with unison passages. People in the region consider these intervals consonant and the resulting sound pleasant and desirable. Singing *ganga* provokes a feeling of corporate unity among singers and (initiated) listeners (Petroviç 1977: 336), and good performances have a strong emotional impact. People in the specified regions generally associate the *ganga* sound with extreme joy. In contrast, the majority of listeners outside the region find the *ganga* sound annoying and even offensive.

The length and content of the lyrics vary greatly among performances. The singers are relatively free in their choice of words, which are often just vocalizations (Petroviç 1977: 144), indicating that words are of far less importance to this genre than to most other types of folk songs. Within its geographical territory, *ganga* is often valued for its distinct sonic effect rather than its semantic content. As it was argued in the case of *mizwij* playing, this effect relies mainly on the manipulation of and contrast between roughness degrees through (often rhythmic) alterations of solo, unison, and minor/major second passages.

The *ganga* style was initially approached by scholars as representing an inability to sing "correctly" (Mariç 1933, in Petroviç 1977: 73). Further research revealed an explicit musical system, characterized by specific rules of musical creation and performance, and surprisingly fine (considering the narrow pitch and dynamic ranges employed) distinctions between substyles and good and bad songs and performances (Rihtman 1951, in Petroviç 1977: 76; Petroviç 1977). Except for some stylized improvisation, *ganga* melodies are thoroughly composed and the principle structural feature of the songs is the contrast between solo and choral sections. This is simulated on a smaller scale in the choral passages through alterations among unisons and minor and major seconds.

The clear intention to achieve expressive goals through explicit use of sounds involving the roughness sensation is illustrated through the *ganga* rules governing a good song or performance:

a) Singers must sing loudly and maintain uniform strength between each other and through time (Petroviç 1977: 45, 101). Combining sound-waves of high and steady intensities results in signals with pronounced amplitude fluctuations and rougher sound.

b) The melodic range must not exceed a major third while harmonic intervals must not exceed a major second (Petroviç 1977: 326). Narrow harmonic intervals give amplitude fluctuation rates within the range corresponding to rougher sounds. The few regions that have increased their range to include wider harmonic intervals produce songs that are considered "impure" and are referred to, with a negative connotation, as "widely sung" (Petroviç 1977: 260).

c) The voices must be as identical as possible, nasal, and without vibrato so that they blend. Perfect blending of voices is a characteristic insisted upon heavily, requiring from the ensemble to "sound as one person" (Petroviç 1977: 308–309). Similar vocal timbres with no vibrato correspond to signals with similar and steady spectral envelopes. This similarity ensures that the resulting degree of amplitude fluctuation and the associated roughness will be maximal. At the same time, nasal timbres correspond to spectra with more energy at the frequency region that human hearing is most sensitive and to more salient roughness sensation.

These loudness and timbral requirements are accompanied by very specific performance arrangements. Singers never move or dance while singing. They stand very tightly together, in an arch, turned slightly towards each other so that their voices will "collide" at the right point (Figure 4). For waves interfering in three dimensions (as is the case with sound waves in air), the geometric condition for maximum interference is collinearity (that is, waves moving along the same line; Westervelt 1957, in Beyer, 1999: 317). This condition is always satisfied for sound waves originating in the same source. For more than one source, such as a choral ensemble, a performance arrangement such as the one found in *ganga* singing does satisfy the collinearity requirement. If the above conditions are not fulfilled "the *ganga* will not be good" (Petroviç 1977: 113). Performers refuse to sing under different conditions or to perform individual parts from the choral sections (when asked by researchers) since, when stripped from their perceptually rough intervals, these lines apparently "make no sense" (Petroviç 1977: 117). In other words, *ganga* represents a rare folk vocal genre where the sense of a song is related more to its sound than to its lyrics. Moreover, the conditions for a good song that makes sense are also conditions that guarantee the perceptual salience of amplitude fluctuations and of the roughness sensation. This relationship is illustrated further by the three types of choral sections found in *ganga* songs:

a) Two to three voice parts sing in minor and major seconds with periodic insertions of unisons, always resolving on a major second. The unisons are not inserted randomly. Their function is to create specific rhythmic effects through the sudden contrast between perceptual roughness and smoothness.

Figure 4. Members of the Balkan Music Ensemble
(University of California, Los Angeles,
Ethnomusicology Department)
performing a *ganga* song.

Petroviç (1977: 288–294) includes a list of such rhythmic effects that are relatively consistent across the *ganga* territory.

b) Voices move in parallel seconds without unison insertions.

c) The leading (lower) part may cross the accompaniment and move a major second above it rather than remain, as is more often the case, below it. There are no cases of voices in contrary motion.

Although most songs start with a solo passage, performers refer to the entry of the choral section as the beginning of the song, and the importance of this section is closely related to its potential for roughness variations.

Ganga singing provides a striking example of a musical tradition that has developed performance techniques and practices that highly correspond to perceptual roughness considerations. This genre's expressive musical vocabulary relies heavily on the sonic effects produced through the manipulation of roughness degrees, and its aesthetic attitudes towards the roughness sensation are in sharp contrast to those of the Western art musical tradition. Along with the other examples cited, it indicates that auditory roughness and its study have musical significance that extends far beyond Western tradition's concern with consonance and dissonance.

5. Roughness Estimation Models

5.1 Existing Models Quantifying Roughness and Their Drawbacks

Having established the musical significance of the roughness sensation, one way to proceed is to devise a model that would systematically quantify the roughness degree of a given sound, permitting the empirical testing of hypotheses that link roughness to musical variables. For example, a roughness estimation model would permit the empirical examination of claims linking a) roughness to dissonance within the Western musical tradition, b) roughness profiles to patterns of tension and release in Near Eastern or North Indian musical pieces (as intended by performers and/or perceived by listeners), or c) to rhythmic effects found in Balkan folk songs.

The two principal studies that have systematically examined the sensation of roughness (von Békésy 1960: 344–354; Terhardt 1974) have, to a large extent, been ignored by existing models quantifying auditory roughness of complex spectra. Numerous such models have been proposed over the last ~100 years (for example. Helmholtz 1885; Plomp and Levelt 1965; Kameoka and Kuriyagawa, 1969a, b; Hutchinson and Knopoff 1978; Sethares 1998). They have been employed in later studies that mainly link roughness to sensory consonance[10] (for example, Bigand *et al.* 1996; Vos 1986; Dibben 1999), demonstrating a relatively low degree of agreement between predicted and experimental data.

All the above models misrepresent the contribution of the amplitudes of the interfering sines (and therefore of the degree of amplitude fluctuation of the resulting complex signal) to the degree of roughness.[11] Usually, the roughness estimation function for a sine-pair (with amplitudes A_1 and A_2) is multiplied by the product of the two amplitudes ($A_1 * A_2$), ensuring minimum roughness if either of the amplitudes approaches zero. This, however, severely overestimates the increase in roughness with increasing amplitudes and, most importantly, fails to capture the relationship between the amplitude difference of two sines close in frequency and the salience of the resulting beats/roughness.

Correct estimation of the roughness degree of a pair of sines or of any arbitrary spectrum is necessary before some claimed link between roughness and an acoustic, perceptual, or musical variable can be systematically tested.

5.2 A New Roughness Estimation Model for Complex Spectra

Existing roughness estimation models do not adequately account for the roughness contribution of amplitude fluctuation, they often fail to capture reliably the effect of pitch register on roughness, and demonstrate a relatively low degree of agreement between predicted and observed roughness levels (for details see Vassilakis 2001, Section 5.3). Based on the roughness-estimation model introduced by Sethares (1998), a new model that includes a term to account for the contribution of the amplitudes of interfering sines to the roughness of a sine-pair has been proposed (Vassilakis 2001, Section 6.4.1).[12] This new term is based on existing experimental results (von Békésy 1960; Terhardt 1974), adjusted to account for the quantitative difference between amplitude modulation depth and degree of amplitude fluctuation (Vassilakis 2001, Chapter 3). The model estimates the roughness of complex spectra with more than two sine components by adding the roughness of the individual sine-pairs. Although it has been argued that the total roughness can be less than the sum of the roughness of each sine-pair (von Békésy 1960: 350–351), pilot experiments indicated otherwise confirming results from previous studies (Terhardt 1974; Lin and Hartmann 1995). The proposed model does not account for the influence of phase on roughness

(Pressnitzer and McAdams 1999) and is not fit to handle continuous spectra. For more details on this and earlier roughness models and for improvement suggestions, see Vassilakis 2001 (Sections 5.3, 6.4.1, & 6.4.2).

6. Roughness Degrees and Harmonic Interval Dissonance Ratings in the Western Musical Tradition

6.1 Introduction

Roughness estimation models have to date been applied mainly to address issues of consonance/dissonance within the Western musical tradition. For comparison purposes, the proposed model was also applied to the issue of consonance, testing the following hypothesis:

> For musicians within the Western musical tradition, roughness ratings of harmonic intervals agree with the roughness degrees estimated using the proposed roughness estimation model (Vassilakis 2001, Section 6.4.1) and correlate with the dissonance degrees suggested by Western music theory. Additionally, dissonance ratings correlate with roughness degrees indicating that, in the Western musical tradition where sensory roughness is in general avoided as dissonant, the consonance hierarchy of harmonic intervals corresponds mainly to variations in roughness degrees (Vassilakis 2001, Section 6.4.3).

Helmholtz (1885), Pratt (1921), and others conducted somewhat similar experiments that compared roughness-model estimations or roughness ratings to music-theory claims. Vassilakis (2001) was the first to examine simultaneously the relationship among roughness model estimations, roughness ratings, dissonance ratings, and Western music theory claims.

6.2 Methods

The thirteen harmonic intervals of the chromatic scale, starting on middle C (C4; fundamental frequency: 256Hz; equal temperament), served as experiment stimuli. The intervals where constructed using digitally synthesized complex tones with slightly detuned sawtooth spectra ($A_n = A_1/n$; A_n: amplitude of the nth component) and six components each.

Along with the predictions of the proposed model, the predictions of two earlier roughness estimation models (Helmholtz 1885: 332; Hutchinson and Knopoff 1978: 17–23) were examined for comparison purposes. All models assume sawtooth spectra and the same starting note, C4. Both earlier models assume ten- rather than six-component complex tones. The Hutchinson and Knopoff model is based on Helmholtz's model, modified to reflect the results by Plomp and Levelt (1965) regarding the effect of pitch register on roughness. Plomp and Levelt examined this effect using six-component complex tones. Therefore, Vassilakis (2001) opted for the use of six- rather than ten-component complex tones.

Intervals were presented randomly to two groups of ten subjects through headphones (same signal in both ears). The first group of subjects was asked to rate the stimuli in terms of roughness, on a scale outlined by the labels: *Not rough–Rough*. The second group of subjects was asked to rate the stimuli in terms of dissonance, on a scale outlined by the labels: *Not dissonant–Dissonant*. Subjects were able to familiarize themselves with the stimuli in a practice experiment. In addition, they demonstrated their understanding of *roughness* in training sessions that included amplitude-modulated sines as stimuli, at various modulation rates and depths and various roughness degrees.

Response scales ranged from 0 (Not Rough/Not Dissonant) to 42 (Rough/ Dissonant). The range (0–42) was based on the roughness of the stimuli calculated using a computer implementation of the proposed model. The predictions of the two comparison models were scaled to fit this range. The experiment was designed and conducted using *MEDS* (Music Experiment Development System) by Kendall (2001). Experiment implementation was automated and experimenter interaction with the subjects was limited to offering initial instructions and administrating training sessions. Subjects entered their responses by moving a scroll bar along the relevant response scales and the scroll-bar starting position was random.

6.4 Results and Discussion

Figure 5 displays the estimated roughness for the thirteen harmonic intervals used in the experiment, based on three roughness estimation models.

The roughness estimates of the proposed model correlate better with the estimates of the Hutchinson and Knopoff model (r = 0.86) than with those of the

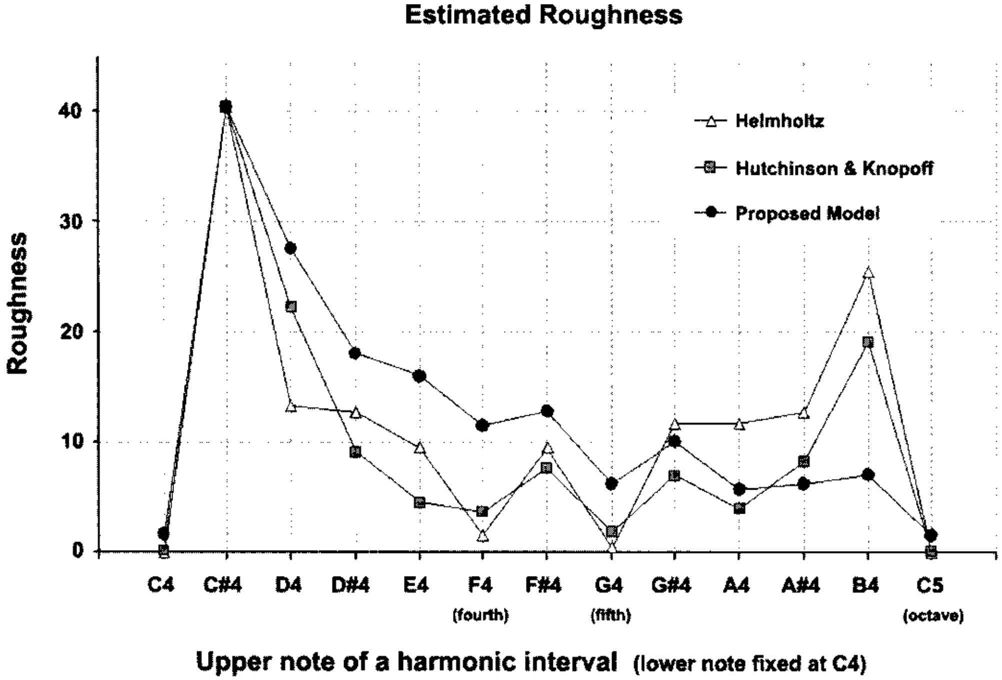

Figure 5. Estimated roughness for all 13 intervals in the chromatic scale starting at C4. Values were estimated using the proposed model and two earlier roughness estimation models by Helmholtz (1885) and Hutchinson and Knopoff (1978).

Helmholtz model ($r = 0.72$). ("Perfect" correlation corresponds to $|r| = 1.0$.) The main reason for this difference is that the Hutchinson and Knopoff model accounts for the effect of pitch register on roughness while the Helmholtz model does not.

Based on Figure 5, a number of differences among the roughness predictions of the three models can be identified:

a) The proposed model predicts a much lower roughness level for the major-seventh interval (C4–B4) than the other two models.
b) The Helmholtz and the Hutchinson and Knopoff models predict lower roughness levels than the proposed model for the intervals between major second (C4–D4) and fifth (C4–G4).
c) Contrary to the earlier models, the proposed model predicts the augmented-fourth interval (C4–F#4) to be smoother than the major third (C4–E4).
d) The proposed model results in a relatively linear roughness curve between the minor second (C4–C#4) and octave (C4–C5) intervals, without the pronounced contrasts found in the roughness curves of the other models.
e) Lastly, the proposed model predicts slightly higher roughness levels for the unison (C4–C4) and octave (C4–C5) intervals than the other models.

The slightly higher roughness levels predicted for the unison and octave intervals by the proposed model are due to the slight detuning applied to the experimental stimuli. The Helmholtz and the Hutchinson and Knopoff models assume perfectly harmonic spectra that bring the roughness levels of unisons and octaves very close to zero.

All other differences (including the difference in the roughness ranking of the augmented fourth [C4–F#4] among the three models) can be explained in terms of the different assumptions each model makes regarding the contributions of degree of amplitude fluctuation and of sound pressure level to roughness. The Helmholtz and the Hutchinson and Knopoff models overestimate the contribution of sound-pressure level and underestimate the contribution of amplitude-fluctuation degree (Vassilakis 2001). This results in overestimating the roughness contribution of some sine-pairs, while underestimating the roughness contribution of others. The higher roughness of the fourth interval relative to the major seventh, predicted by the proposed model, is consistent with experiments indicating that fourths are less likely to be perceived as single tones (less prone to tonal fusion) than major sevenths (DeWitt and Crowder 1987, in Huron 1991: 136).[13] The somewhat linear shape of the proposed model's roughness curve is due to the progressive decrease in *AF-degree* for the sine-pairs that contribute the most to the roughness of each interval, as intervals widen. As the intervals get wider, the amplitude difference of the closely interacting sine components gets larger and the *AF-degree* gets smaller.

Figure 6 displays the mean responses and standard deviations of the subject-groups rating the stimuli in terms of roughness and dissonance.

Dissonance responses correlated well with roughness responses ($r = 0.94$), indicating that changes in dissonance among the thirteen intervals corresponded to changes in roughness. This suggests that the presence of roughness provides an important clue for dissonance judgments of isolated harmonic intervals.

Analysis of variance suggested that subjects rating dissonance used slightly different criteria than subjects rating roughness (analyses were performed using *Statistica*

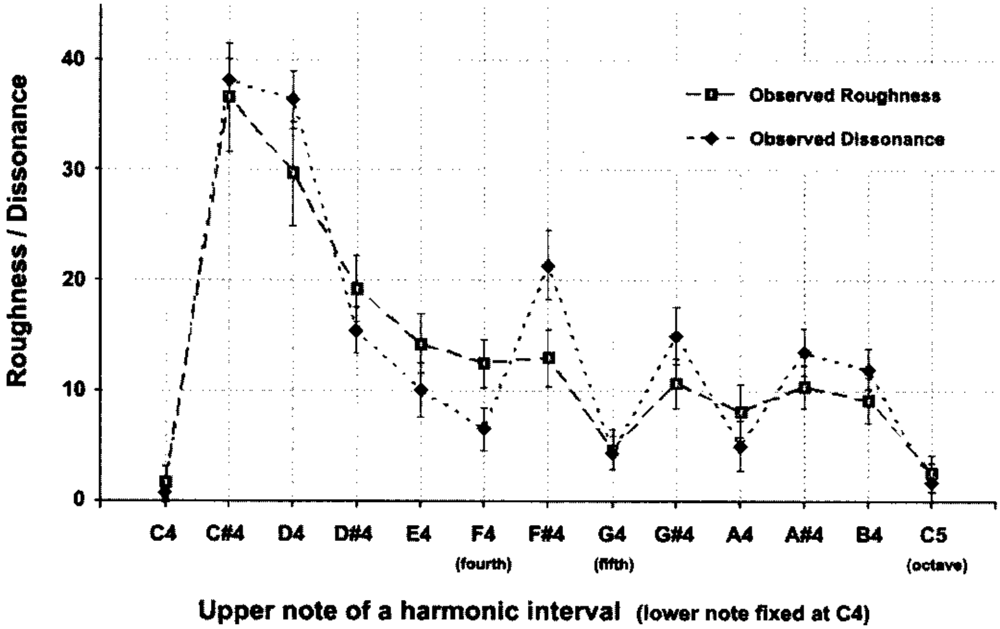

Figure 6. Mean observed roughness and dissonance for
all thirteen intervals in the chromatic scale starting at C4
(10 subjects per group—error bars: ± 1 standard deviation).

5.5 for Windows, StatSoft, Inc., 2000). Post-hoc analysis indicated that this difference was manifested the strongest in the ratings of the augmented-fourth, the perfect-fourth, and the minor-sixth intervals. The perfect-fourth interval was judged more rough than dissonant while the augmented-fourth and minor-sixth intervals were judged more dissonant than rough.

To investigate further the observed differences, two separate analyses were performed on the means obtained from the "roughness" and the "dissonance" subject-groups, organizing the intervals into the roughness and dissonance categories displayed in Table 1.

Table 1 indicates similarities as well as differences between the roughness and dissonance ratings of the thirteen harmonic intervals, and will be examined in some detail. When subjects make dissonance judgments they do not necessarily rely on strictly acoustical criteria. Cultural conditioning has been introduced as an explanation to the consonance/dissonance concept since the 1940s (for example, Cazden 1945, in Sethares 1998: 78–79). At the same time, the historical tension between sedimentation and innovation within a musical tradition has supported what Helmholtz recognized as continuously changing attitudes towards consonance and dissonance (Helmholtz 1885: 84–85). Therefore, historical and cultural criteria must be included along with physical, physiological, and psychological ones when trying to explain dissonance judgments.

Table 1
Mean roughness and dissonance ratings grouped according to statistical significance by Tukey HSD post-hoc comparisons

Roughness			Dissonance		
Category	Interval	Mean Roughness	Category	Interval	Mean Dissonance
1	Unison	1.7	1	Unison	0.8
1	Octave	2.5	1 - 2	Octave	1.7
1 - 2	Perfect Fifth	4.7	2 - 3	Perfect Fifth	4.4
2 - 3	Major Sixth	8.2	3	Major Sixth	5.1
3 - 4	Major Seventh	9.2	3	Perfect Fourth	6.6
3 - 4 - 5	Minor Seventh	10.4	4	Major Third	10.1
3 - 4 - 5	Minor Sixth	10.7	4 - 5	Major Seventh	12
4 - 5	Perfect Fourth	12.5	5 - 6	Minor Seventh	13.5
4 - 5	Aug. Fourth	13	5 - 6	Minor Sixth	15
5	Major Third	14.3	6	Minor Third	15.5
6	Minor Third	19.2	7	Aug. Fourth	21.4
7	Major Second	29.7	8	Major Second	36.4
8	Minor Second	36.6	8	Minor Second	38.2

As a first observation, the intervals in Table 1 are grouped into eight roughness and eight dissonance categories. However, there is less overlap in the dissonance categories, indicating that subjects rated dissonance with more confidence than they rated roughness. As opposed to the short history of the concept of roughness, limited within areas outside the mainstream music disciplines, the concept of dissonance has had a long tradition in Western music discourse (Hutchinson and Knopoff 1978: 1; Sethares 1998: 73–80). It should therefore be expected that subjects would be more familiar with the concept of dissonance than with the concept of roughness and would make dissonance ratings with more confidence. The experiment results support this suggestion and show signs of categorical perception for dissonance, while roughness ratings seem to have been made along a continuum.

The extremes of the two rating scales in Table 1 are occupied by the same intervals, indicating that the clear presence or absence of roughness dominates dissonance decisions. At the same time, the roughness differences among these harmonic intervals are larger than their dissonance differences. This reduced resolution in the dissonance ratings at the extremes of the scale is consistent with Western culture's preference for smooth sounds over rough ones, offers one more indication of categorical perception for dissonance, and suggests a possible difference-threshold for the dissonance/annoyance level of roughness that needs to be systematically examined in a future study.

For intervals located closer to the middle of the rating scale, roughness ratings become increasingly ambiguous (increasing overlap among roughness categories). Dissonance ratings, on the other hand, become increasingly categorical, demonstrating differences larger than those found in the roughness ratings (for example, see the relationship among the augmented-fourth, perfect-fourth, major-third, and minor-third intervals). When the roughness of an interval is neither very large nor very small, dissonance decisions appear to be based on clues additional to roughness, occasionally ignoring roughness altogether (for example, see the relationship between the augmented-fourth and perfect-fourth intervals).

The high dissonance rating of the augmented-fourth interval (in spite of its low roughness level compared to the major third) and the overall higher dissonance ratings of minor over major intervals (regardless of their roughness ratings) indicate that, when there is no clear presence/absence of roughness, dissonance decisions are not based on acoustical cues. Rather, they may be culturally and historically mediated. The augmented fourth is the only interval within the chromatic scale that is not found in the harmonic series and cannot be arrived at through integer divisions of a string. The mathematical impossibility of the augmented-fourth interval, along with the long-standing link between mathematics and music, may have provided the original basis for the unfavorable aura that has followed this interval for centuries. The clear separation between major and minor intervals in the dissonance ratings along with the strong Western-based association of dissonance with unpleasantness reflect a dislike for minor sonorities so ingrained within the Western tradition that is already present in pre-language children (Kastner and Crowder 1990). The culture-specific nature of this attitude, however, is indicated by the increase in the distinction between major and minor with age (that is, minor becomes increasingly "negative" the longer one is exposed to a "pro-major" tradition) and is fully exposed through encounters with musical traditions where minor harmonies are considered joyful, as is the case with the music of the Andean highlands of Peru (Turino 1993: 43–58).

The results, therefore, indicate that roughness constitutes a significant but not the sole factor guiding listeners in their dissonance judgments. In terms of existing theoretical models, the dissonance ranking of the intervals obtained from the experiment agrees best with Stumpf's ranking (1898, in Davies 1978: 158) except for the major-seventh interval, which was rated less dissonant than predicted by all models other than the proposed model. Stumpf's dissonance ranking was based on his concept of *fusion*. The fusion hypothesis was excluded from the present study because it is based on a large number of interacting and hard-to-quantify variables and does not provide a readily measurable physical correlate for dissonance.

For a more detailed examination of the three models addressed in this study, Figures 7, 8, and 9 compare the observed roughness and dissonance levels to the roughness values estimated by each model (for details on the statistical analysis of the data see Vassilakis 2001, Section 6.4.3).

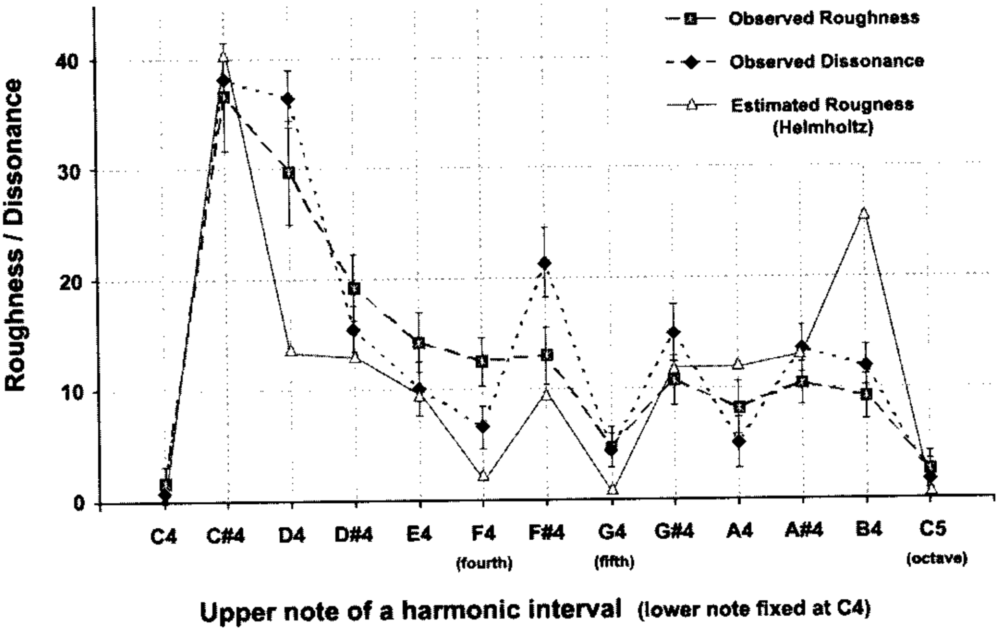

Figure 7. Estimated roughness (Helmholtz 1885) versus observed roughness and observed dissonance for all thirteen intervals in the chromatic scale starting at C4.

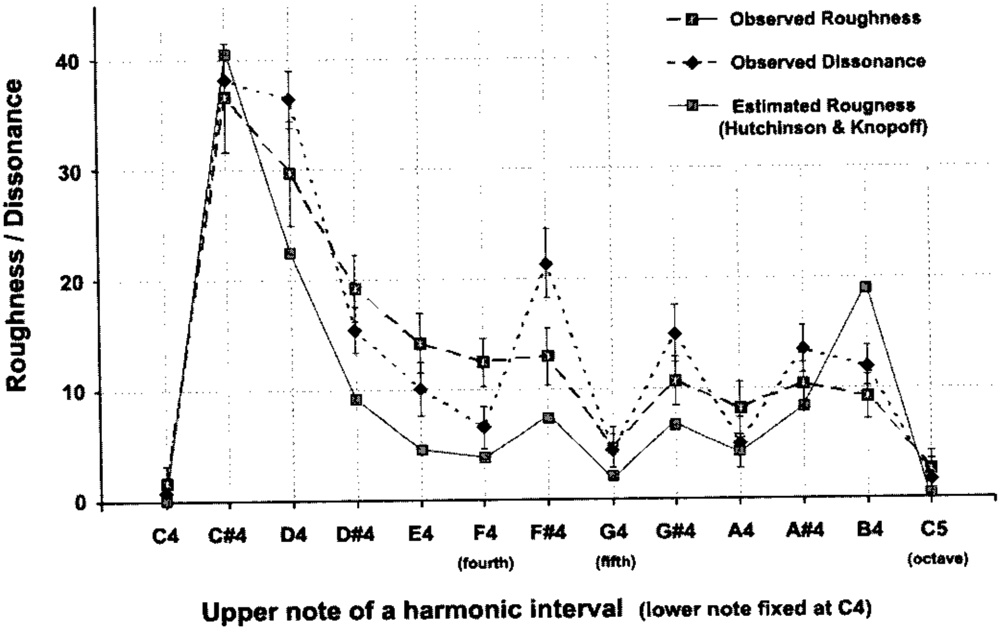

Figure 8. Estimated roughness (Hutchinson and Knopoff 1978) versus observed roughness and observed dissonance for all thirteen intervals in the chromatic scale starting at C4.

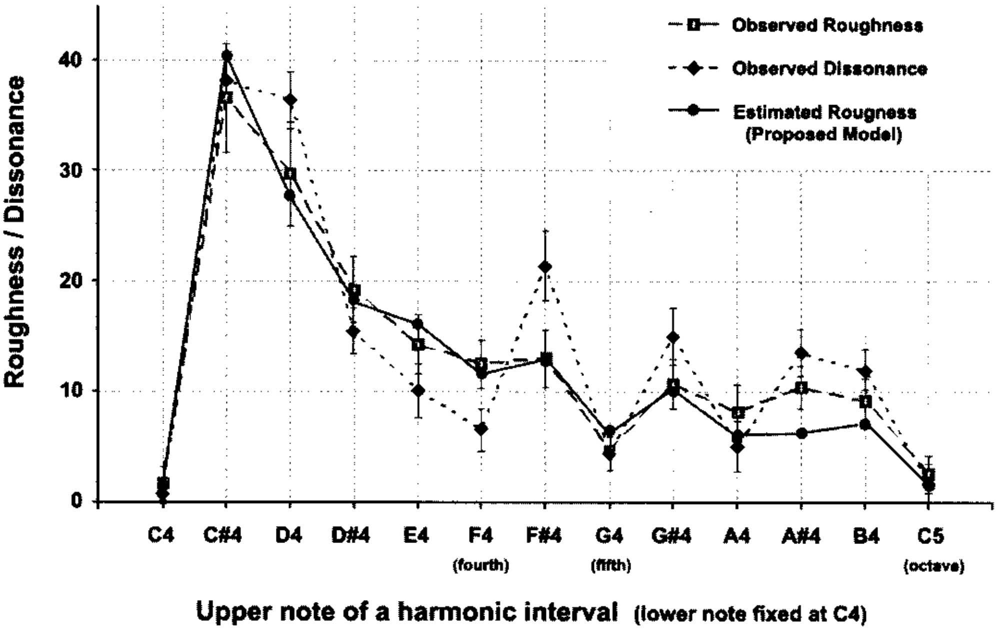

Figure 9. Estimated roughness (proposed model) versus observed roughness and observed dissonance for all thirteen intervals in the chromatic scale starting at C4.

The proposed model demonstrates the best agreement between estimated and observed roughness ($r = 0.98$) as well as between estimated roughness and observed dissonance ($r = 0.91$). With the exemptions discussed previously, observed dissonance also correlates well with observed roughness ($r = 0.94$).

The results support the claim that, in the Western musical tradition where sensory roughness is avoided as dissonant, the consonance hierarchy of isolated harmonic intervals corresponds mainly to variations in roughness degrees, with subtle roughness variations being, in general, ignored. As the presence/absence of roughness become less pronounced, sensory dissonance/consonance gives way to alternative criteria for dissonance judgments. Tenney (1988, in Sethares 1998: 73–76) discusses five distinct ways in which the consonance and dissonance concept has been understood in music, none of which makes any direct reference to the cultural or the historical dimension of dissonance. The results of the present study suggest that in the absence of strong sensory cues, dissonance judgments of isolated harmonic intervals appear to be culturally and historically mediated. Such a conclusion is consistent with the highly varied attitudes around the world towards the roughness sensation, presented in this study. As has been demonstrated, roughness may in some cases even be considered "consonant," with roughness variations being credited as responsible for sonic, structural, semantic, and expressive aspects of musical pieces. The proposed roughness estimation model provides the means to examine empirically such claims, offering opportunities for further study.

7. Summary and Conclusions

Examination of musical instrument construction and performance practices from around the world illustrates the musical relevance of the roughness sensation and indicates that sound variations involving this sensation are found in many musical traditions. The use of rough sounds helps create a buzzing (Indian *tambura* drone) or rattling (Bosnian *ganga* singing) sonic canvas that becomes the backdrop for further musical elaboration. It permits the creation of timbral variations (Middle Eastern *mijwiz* playing) and rhythmic variations (*ganga* singing) through gradual or abrupt changes among roughness degrees. Whether such variations are explicitly sought after (as in *ganga* singing and *mijwiz* playing) or are introduced more subtly and gradually (as may be the case in the typical chord progressions/modulations of Western music), they appear to form an important part of a musical tradition's expressive vocabulary.

Models estimating the roughness degree of musical sounds have been developing since the end of the nineteenth century. Existing roughness estimation models, however, do not account for the roughness contribution of amplitude fluctuation, they often fail to capture reliably the effect of pitch register on roughness, and demonstrate a relatively low degree of agreement between predicted and observed roughness levels. It is argued that a new roughness estimation model (Vassilakis 2001) better represents the theoretical knowledge and experimental results on sensory roughness and is better fit to test hypotheses linking the roughness sensation to musical variables than are existing models.

The proposed model is compared to two earlier roughness estimation models (Helmholtz 1885; Hutchinson and Knopoff 1978), indicating several differences in prediction. For example, the proposed model estimates much lower roughness values than the other models for the major seventh and the augmented fourth intervals. The majority of differences in the predictions of the three models can be explained in terms of the different assumptions each model makes regarding the contributions of degree of amplitude fluctuation and of sound pressure level to roughness.

An experiment (Vassilakis 2001, Section 6.4.3) rating isolated harmonic intervals in terms of roughness and dissonance is discussed and the results are compared against the predictions of the three models. The proposed model demonstrates the best agreement between estimated and observed roughness, as well as between estimated roughness and observed dissonance. The results indicate that, within the Western musical tradition, the clear presence or absence of roughness in the sound of an interval dominates dissonance ratings. When the roughness is neither very large nor very small, decisions on dissonance often ignore roughness and appear to be culturally and historically mediated. Overall, dissonance ratings correlate well with roughness ratings, indicating that, in the case of isolated harmonic intervals, the sensation of roughness is the primary cue guiding dissonance judgments. The results also support the hypothesis that, in the Western musical tradition where sensory roughness is in general avoided as dissonant, the consonance hierarchy of harmonic intervals corresponds to variations in roughness degrees. Further study should include cross-cultural empirical investigations.

NOTES

1. Portions of this work were presented at the 142nd meeting of the Acoustical Society of America.

2. The author would like to thank Professors R. A. Kendall, R. W. H. Savage, A. J. Racy, and N. A. Jairazbhoy (University of California, Los Angeles, Department of Ethnomusicology) for reading early versions of this manuscript and offering valuable suggestions.

3. A *sine signal* is a signal with a sinusoidal shape. Such a signal represents the simplest type of vibration, called simple harmonic motion (similar to a free pendular motion). The wave originating from a simple harmonic motion is also represented by a sine signal and is called *sine wave*. When a sine wave with frequency and amplitude values within the auditory limits reaches the ear, it gives rise to the sensation of a *pure tone* (that is, a tone similar to the sound produced by a tuning fork or an electric sine-wave generator).

4. The term *complex tone* refers to the sensation arising from sound waves represented by complex signals. Any signal that does not have a sinusoidal shape is called *complex*. Fourier (early 1800s) proved that complex signals can be analyzed mathematically into the sum of a set of sine signals. These are called the Fourier or spectral components of a given complex signal and make up the complex signal's *spectrum*. Analysis of a complex signal into sine components is called Fourier analysis, while the reverse process, constructing a complex signal out of a set of sines, is called Fourier synthesis. For periodic signals (such as the signals corresponding to most musical sounds), the lowest frequency component is called the fundamental and all components have frequencies that are integer multiples of the frequency of the fundamental. That is, if the fundamental has frequency f, then the components have frequencies $1f, 2f, 3f, 4f$, and so forth. Such complex signals are also called harmonic; all other signals are called inharmonic. The pitch of a harmonic signal matches in frequency the frequency of the fundamental (whether or not the fundamental component is actually present in the signal's spectrum).

5. The roughness sensation is not necessarily linked to the addition of two or more tones. It can also arise from the interference among the components of a single complex tone or from performance practices in monophonic music (for example, fast vibrato, reed rattling in woodwinds, and vocal techniques). The only condition is that the resulting complex signal exhibits amplitude fluctuations within the specified range of fluctuation rates.

6. The term *combination tones* was introduced by Helmholtz in the late 1800s to describe tones that can be traced not in a vibrating source but in the combination of two or more waves originating in independent vibrating sources. A specific combination tone, the difference tone, is one of the perceptual manifestations of amplitude fluctuation. Combination tones are the products of wave interference and have significant physical origins along with physiological, neurological, and cognitive ones. The physical origins of combination tones can be attributed to the transfer characteristics of the wave propagation medium. For sound waves propagating in air, the physical origin of combination tones is based on the following asymmetry: *effective propagation velocity* (c_{ef}) > *velocity of sound in air* (c_0) in condensations and $c_{ef} < c_0$ in rarefactions (noted in 1808 by Poisson and in 1860 by Riemann, and cited in Beyer 1999: 40 and 148–149, respectively).

7. Kendall *et al.* (1999) have argued that the degree of a sound's "nasality" constitutes the primary dimension of timbre. They quantify "nasality" in terms of *spectral centroid*, a measure of the energy distribution and time-variancy in the spectrum of a complex signal. The present study considers roughness another important dimension of timbre and references an appropriate roughness measure.

8. This attitude dates back to the ancient Greeks and the Pythagorean conception of harmony. To date, no study has systematically examined the origin and history of Western tradition's deep dislike towards rough sounds.

9. Loaded with festive and ecstatic connotations, the *mijwiz* is hailed for inspiring "strong passions and exerting compelling powers and energies" (Racy 1994: 50). The buzzing, rough sound of another double-pipe, the ancient Greek *aulos*, was prominent in cult rituals (Marcuse 1975: 56).

10. The term *sensory consonance* was introduced by Plomp and Levelt (1965) to refer to consonance understood specifically as absence of roughness. In more general terms, the concept of consonance has been loaded with all kinds of associations/connotations. Similarly to timbre, consonance seems to have been a wastebasket of aesthetic and evaluative judgments in music, as well as the source of justification arguments regarding general stylistic trends or specific compositional decisions. The term "wastebasket" is used as a reference to Bergman's (1990: 93) assessment that timbre seems to be the wastebasket of all sound characteristics that cannot be placed under the labels of pitch or loudness.

11. If two sines with different frequencies f_1, f_2, $(|f_1 + f_2|/2 >> |f_1 - f_2|/2)$ and amplitudes A_1, A_2 $(A_1 \geq A_2)$ are added together, the amplitude of the resulting signal will fluctuate between a maximum $(A_{max} = A_1+A_2)$ and a minimum $(A_{min} = A_1-A_2)$ value. The degree of amplitude fluctuation (AF_{degree}) is defined as the difference between the maximum and minimum amplitude values relative to the maximum amplitude value. So, $AF_{degree} = (A_{max} - A_{min})/A_{max} = 2A_2/(A_1+A_2)$. Degree of amplitude fluctuation, therefore, depends less on the absolute and more on the relative amplitudes of interfering sines.

12. According to the proposed model, the roughness $\boldsymbol{R}$ of pairs of sines with frequencies f_1 & f_2 $(f_2 \geq f_1)$, amplitudes A_1 & A_2 $(A_1 \geq A_2)$ and equal initial phases is: $\boldsymbol{R} = \mathbf{X}^{0.1} * \mathbf{Y}^{3.11} * \mathbf{Z}$. $\mathbf{X} = A_1 * A_2$, represents the dependence of roughness on intensity (amplitude of the added sines); $\mathbf{Y} = 2A_2/(A_1+A_2)$, represents the dependence of roughness on amplitude fluctuation degree (amplitude difference of the added sines); $\mathbf{Z} = e^{-b1s(f2 - f1)} - e^{-b2s(f2 - f1)}$, represents the dependence of roughness on amplitude fluctuation rate (frequency difference of the added sines) and register (average frequency of the added sines), with $b_1 = 3.5$, $b_2 = 5.75$, $s = 0.24/(s_1 f_1 + s_2)$, $s_1 = 0.0207$, & $s_2 = 18.96$. For more details see Vassilakis (2001, Sections 6.4.1 and 6.4.2).

13. The fusion of two simultaneous tones is proportional to the degree to which the tones are heard as a single perceptual unit. According to Stumpf, fusion is the basis of consonance (Stumpf 1898 in Sethares 1998: 77).

REFERENCES

Békésy, G. von
1960 [1989] *Experiments in Hearing.* New York: Acoustical Society of America Press.

Bergman, A.
1990 *Auditory Scene Analysis.* Cambridge, MA: MIT Press.

Beyer, R. T.
1999 *Sounds of Our Times. Two Hundred Years of Acoustics.* New York: AIP Press; Springer-Verlag.

Bigand, E., Parncutt, R., and Lerdahl, F.
1996 "Perception of musical tension in short chord sequences: The influence of harmonic function, sensory dissonance, horizontal motion, and musical training." *Perception and Psychophysics* 58: 125–141.

Campbell, M. and Greated, C.
1987 *The Musician's Guide to Acoustics.* New York: Schirmer Books.

Carlton Maley, V. Jr.
1990 *The Theory of Beats and Combination Tones, 1700–1863.* [Harvard Dissertations in the History of Science. O. Gingerich, editor]. New York: Garland Publishing.

Carterette, E. C., Vaughn, K., and Jairazbhoy, N. A.
1989 "Perceptual, acoustical, and musical aspects of the Tambura drone." *Music Perception* 7(2): 75–108.

Davies, J. B.
1978 *The Psychology of Music.* Stanford: Stanford University Press.

Dibben, N.
1999 "The perception of structural stability in atonal music: The influence of salience, stability, horizontal motion, pitch commonality, and dissonance." *Music Perception* 16(3): 265–294.

Fletcher, N. H. and Rossing, T. D.
1998 *The Physics of Musical Instruments.* 2nd ed. New York: Springer-Verlag.

Gadamer, H. G.
1989 [1960] *Truth and Method.* 2nd edition. New York: Continuum. [*Wahrheit und Methode,* 1960. Tubingen, trans. J. Weinshamer and D. Marshall.]

Hashimoto, T. and Hatano, S.
1994 "Roughness level as a measure for estimating unpleasantness: Modification of roughness level by modulation frequencies." *Proceedings of the Inter-Noise 94 Conference.* Yokohama, Japan, pp. 887-892.

Helmholtz, H. L. F.
1885 [1954] *On the Sensations of Tone as a Physiological Basis for the Theory of Music.* 2nd English edition. New York: Dover Publications. [*Die Lehre von den Tonempfindungen,* 1877. 4th German edition, trans. A. J. Ellis.].

Hindemith, P.
1945 *The Craft of Musical Composition.* New York: Associated Music Publishers Inc. [4th edition,trans. A. Mendel.]

Huron, D.
1991 "Tonal consonance versus tonal fusion in polyphonic sonorities." *Music Perception* 9(2): 135–154.

Hutchinson, W. and Knopoff, L.
1978 "The acoustic component of Western consonance." *Interface* 7: 1–29.

Imaizumi, S.
1986 "Acoustic measures of roughness in pathological voice." *Journal of Phonetics* 14 (3/4): 457–462.

Jairazbhoy, N. A.
1995 *The Rāgs of North Indian Music. Their Structure and Evolution.* 2nd ed. Bombay, India: Popular Prakashan.

Kameoka, A. and Kuriyagawa, M.
1969a "Consonance theory, part I: Consonance of dyads." *Journal of the Acoustical Society of America* 45(6): 1451–1459.

1969b "Consonance theory, part II: Consonance of complex tones and its calculation method." *Journal of the Acoustical Society of America* 45(6): 1460–1469.

Kastner, M. P. and Crowder, R. G.
1990 "Perception of the major/minor distinction: IV. Emotional connotations in young children." *Music Perception* 8: 189–201.

Kendall, R. A.
2001 "Music Experiment Development System (MEDS) 2001B for Windows." Los Angeles: University of California Los Angeles, Department of Ethnomusicology, Program in Systematic Musicology.

Kendall, R. A., Carterette, E. C., and Hajda, J. M.
1999 "Perceptual and acoustical features of natural and synthetic orchestral instrument tones." *Music Perception* 16(3): 327–363.

Lin J. Y. and Hartmann, W. M.
1995 "Roughness and the critical bandwidth at low frequency." *Journal of the Acoustical Society of America* 97(5/2): 3274.

Marcuse, S.
1975 *A Survey of Musical Instruments.* New York: Harper and Row.

Nederveen, C. J.
1998 *Acoustical Aspects of Woodwind Instruments.* 2nd ed. DeKalb: Northern Illinois University Press.

Ortmann, O.
1922 "The sensorial basis of music appreciation." *Journal of Comparative Psychology* 2: 227–256.

Petroviç, A.
1977 "Ganga: A Form of Traditional Rural Singing in Yugoslavia." Unpublished Dissertation. Belfast: University of Belfast; Department of Social Anthropology.

Plomp, R.
1964 "The ear as a frequency analyzer." *Journal of the Acoustical Society of America* 36(9): 1628–1636.

Plomp, R. and Levelt, W. J. M.
1965 "Tonal consonance and critical bandwidth." *Journal of the Acoustical Society of America* 38(4): 548–560.

Pratt, C. C.
1921 "Some Qualitative Aspects of Bitonal Complexes." *American Journal of Psychology* 32: 490–515.

Pressnitzer D. and McAdams, S.
1999 "Two phase effects in roughness perception." *Journal of the Acoustical Society of America* 105(5): 2773–2782.

Pressnitzer, D., McAdams, S., Winsberg, S., and Fineberg, J.
2000 "Perception of musical tension for nontonal orchestral timbres and its relation to psychoacoustic roughness." *Perception and Psychophysics* 62 (1): 66–80.

Racy, A. J.

1994 "A dialectical perspective on musical instruments: the East Mediterranean Mijwiz." *Ethnomusicology* 38(1): 37–58.

Ricoeur, P.

1984 *Time and Narrative, Vol. #1*. Chicago: The University of Chicago Press. [Trans. K. McLaughlin & D. Pellauer.]

Sethares, W. A.

1998 *Tuning, Timbre, Spectrum, Scale*. London: Springer-Verlag.

StatSoft, Inc.

2000 "Statistica 5.5 for Windows." Tulsa, Oklahoma: StatSoft, Inc.

Terhardt, E.

1974 "On the perception of periodic sound fluctuations (roughness)." *Acustica* 30(4): 201–213.

1984 "The concept of musical consonance: A link between music and psychoacoustics." *Music Perception* 1(3): 276–295.

Turino, T.

1993 *Moving Away from Silence: Music of the Peruvian Altiplano and the Experience of Urban Migration*. Chicago: The University of Chicago Press.

Vassilakis, P.

2001 "Perceptual and Physical Properties of Amplitude Fluctuation and their Musical Significance." Doctoral Dissertation. Los Angeles: University of California, Los Angeles; Systematic Musicology.

Vogel, M.

1993 *On the Relations of Tone*. Bonn: Verlag für systematische Musikwissenschaft, GmbH [Lehre von den Tonbeziehungen, 1975. Bonn, trans. V. J. Kisselbach].

Vos, J.

1986 "Purity ratings of tempered fifths and major thirds." *Music Perception* 3(3): 221–258.

Vos, J. and Smoorenburg, G. F.

1985 "Penalty for impulse noise, derived from annoyance ratings for impulse and road-traffic sounds." *Journal of the Acoustical Society of America* 77(1): 193–201.

Zwicker, E.

1961 "Subdivision of the audible frequency into critical bands." *Journal of the Acoustical Society of America* 33(2): 248–249.

Zwicker, E., Flottorp, G., and Stevens, S. S.

1957 "Critical band-width in loudness summation." *Journal of the Acoustical Society of America* 29(5): 548–557.