MUTOR *TiddlyWiki* Unit 4 on Consonance and Dissonance

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Unit4Introduction

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Why do we hate nails on a chalkboard? Why are some sounds rougher than others? The understanding of how and why we perceive dissonance, roughness, and interactions between sounds is fundamental to the understanding of sensation and perception in music. In this unit we will cover the physical and biological aspects of sensory and musical consonance and dissonance. We will start by defining dissonance and introducing the notions of frequency selectivity and the auditory filter, which includes a discussion of the critical band. Then we will explore the contexts in which dissonance and roughness are perceived. Concepts to be introduced are beat frequencies, two-tone interactions, the hierarchy of intervals, and the effects of phase, spatial location, and mistuning on dissonance and roughness. As a tool for composers, this unit will emphasize the implications of the concepts covered on compositional applications such as voice-leading and orchestration. We will also present information on the neurobiology of consonance and dissonance information processing, and the various views of consonance and dissonance by scientists and composers throughout history. Organizationally, this unit can be conceived as moving from a bottom-up view to a top-down view of consonance and dissonance in music perception.

ConceptualizationsofMusicalDissonance

PsycheLoui, 9 June 2006 (created 8 June 2006)

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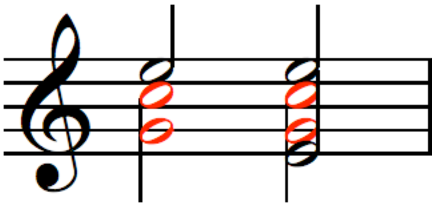
How and why has the concept of dissonance changed throughout the centuries? Let us begin by looking at Pythagorus' understanding of dissonance. Pythagorus found that ratios of whole numbers from 1 to 4 produced consonant intervals: 2:1 = octave, 3:1 = fifth (plus an octave), 4:1 = double octave, 3:2 = fifth, 4:3 = fourth. Ratios of larger whole numbers such as 9:8 (major second) were considered dissonant.

Perhaps the most confusing interval is the perfect fourth, which is considered both consonant and dissonant. According to Pythagorus, the fourth is as consonant as the fifth, but later, the case becomes more complex. In common-practice music, the fourth is considered consonant unless it is formed with the bass note of a sonority, in which case it is considered dissonant and must be prepared and resolved properly. For example, the fourth between the lowest two notes of the first chord of Figure 15 is dissonant, but when supported by the E in the second example, the fourth becomes consonant.



Some of the initial work on understanding dissonance from a physical and perceptual view was done by H. von Helmholtz in the 19th century. After that, it wasn't until the 1930s that von Bekesy made a number of observations on roughness, including the description of roughness as a function of beat frequency. Finally, the study of roughness took off in the 1960s as a topic of psychoacoustical research led by Terhardt, Plomp, and others. It is due to the work of these researchers that the notion of roughness was linked to the critical bandwidth, the resolution of the auditory filter, and amplitude modulation. (Terhardt, 1968)

WhatIsDissonance

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What is Dissonance?
The New Grove Dictionary of Music and Musicians defines dissonance as the "[...] antonym to consonance [...] a discordant sounding together of two or more notes perceived as having 'roughness' or 'tonal tension' ". Even in this short definition, we can see already that there are at least two dimensions to dissonance: the term *roughness* refers to perceptual dissonance, whereas *tonal tension* can only be experienced by a listener acquainted with Western tonal music. But why are some sounds dissonant (e.g. seconds, augmented fourths, etc.) while others aren't (e.g. fifths, octaves, etc.)? Are some sounds more dissonant than others? Can a sound be just a little dissonant? To answer these questions, we need to look at how the ear works.

BasilarMembrane&FrequencySelectivity

PsycheLoui, 8 June 2006 (created 8 June 2006)

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In previous units we have looked at the anatomy of the ear, including the cochlea and its inner structures.

The basilar membrane responds to sound stimulation in the cochlea. It is said to be **tonotopically organized** or organized along a gradient of frequency, i.e. the continuum of frequency from low to high is mapped from one end of the basilar membrane to the other. Sound enters the ear as a pressure wave and is transferred to the basilar membrane causing it to be displaced as seen in figure 1. Many tiny hair cells, which transmit mechanical motion into nerve firings, lie along the length of the basilar membrane. These hair cells are sensitive to different frequencies, with the cells on wider part of the basilar membrane responding to lower frequencies, and those on the narrower part of the basilar membrane selectively tuned to higher frequencies. The basilar membrane can be seen as a filterbank with each filter responding selectively to a certain range of frequencies.

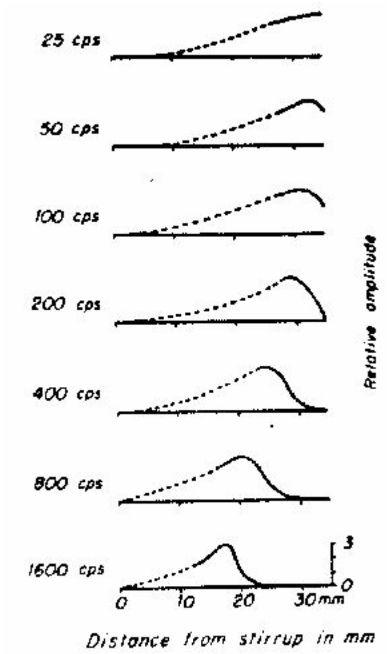

Fig 1. Bekesy's measurement of basilar membrane displacement as a function of frequency and position along the length of the membrane. From: Concerning the pleasures of observing, and the mechanics of the inner ear. Nobel Lecture, December 11, 1961, Georg von Bekesy
(in Nobel Lectures Physiology or Medicine 1942 - 1962, Elsevier, 1964, pp. 722-746).

Bandwidth and Shape of the Auditory Filter

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The frequency resolution of the auditory filter is directly related to the frequency selectivity of the hair cells along the basilar membrane. Extensive psychoacoustical experiments have been conducted in order to measure the bandwidth of the auditory filter, also known as the *critical bandwidth*. Based on these measurements, we are able to build a model of the filter and observe its response to different sounds.
Around middle C (approximately 250Hz) the critical bandwidth of the auditory filter is about 1/3 of an octave wide. (We can, however, differentiate pitch at much higher resolutions -- we will discuss why later.) In lower registers (bass frequencies) the critical bandwidth is wider, spanning up to an octave. Hi-fi audio systems generally use 1/3 octave bands which provide a fairly good match to the resolution of the auditory filter.
Many formulae have been constructed to estimate the width of the critical band as it varies with frequencies. The most accurate of these formulae is the Equivalent Rectangular Bandwidth (ERB), which is given by

$$ERB(f) = 0.108f + 24.7$$

The basilar membrane as a filterbank can be simulated using a bank of gammatone filters. This filterbank is comprised of overlapping bandpass filters that model the critical bands of the basilar membrane. The response of such a filterbank is described by

$$\gamma(t) = at^{n-1} \cdot e^{-2\pi bt \cdot \mathrm{ERB}(f_c)} \cdot \cos(2\pi f_c t + \phi)$$

and can be seen in figure 2. Notice that the filters overlap with one another in order to simulate the continuous frequency response of the basilar membrane.

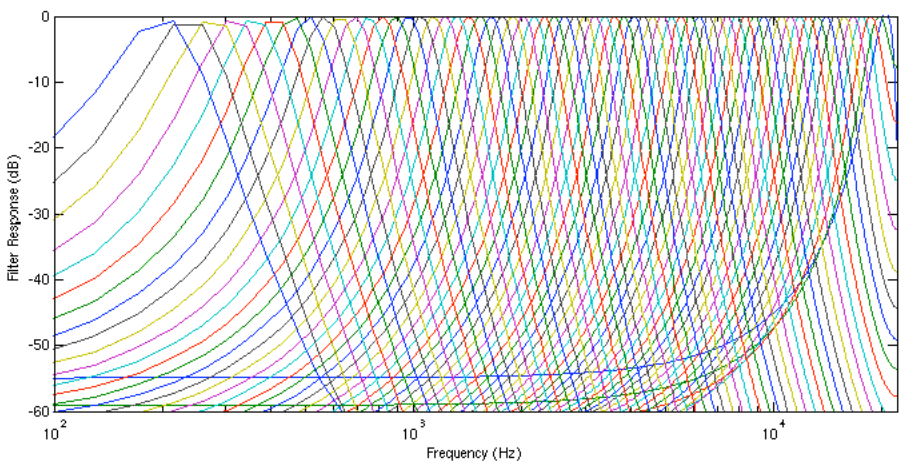

Figure 2. The frequency response of a bank of gamma-tone filters which approximates the frequency response of the basilar membrane.

Resolving Two Components: Beats and Interactions

PsycheLoui, 9 June 2006 (created 8 June 2006)

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To what extent can you resolve two components? How close together do they have to be before they start interacting and beating?

Consider two tones, one fixed at A4 (440. Hz) and another moving smoothly from A3 (220. Hz), an octave below the fixed tone, to A5 (880. Hz), an octave above the fixed tone. When the distance separating these two tones is less than a critical band, they will fuse together into a single percept and we will hear beating and roughness. Figure 3 shows the fixed and moving tones along the x and y axes respectively. When the two tones are within a critical band, the perceived frequency is approximately the average of the the two tones and we hear roughness on the outskirts of the critical band which becomes beating as the moving tone approaches the frequency of the fixed tone.

CriticalBandwidth

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Critical bandwidth

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As we mentioned above, the critical bandwidth (ERB) is the frequency region within which two tones interact - i.e. produce the sensations of roughness and beating, and fuse together into a single percept (refer to figure 3 from the previous lesson). As mentioned above, the ERB is defined by Moore and Glasberg [1] as

$$ERB(f) = 0.108f + 24.7$$

As this formula implies, the critical bandwidth varies in size and can be quite large in the low register. Figure 4 shows how the ERB varies in size from 20Hz to 20kHz.

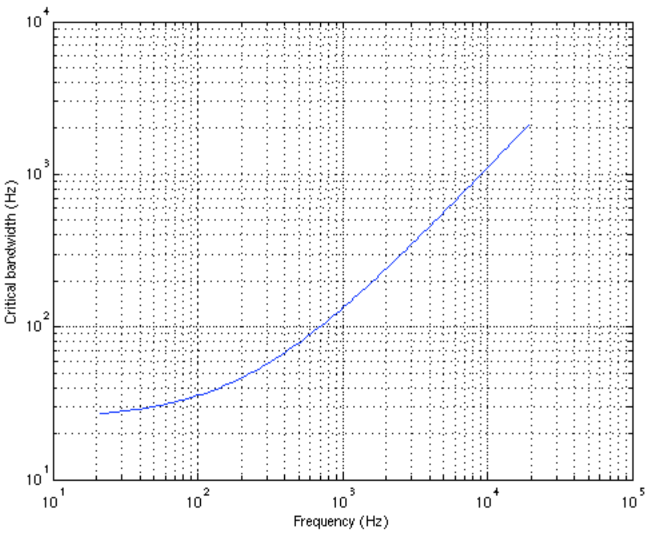

Figure 4. The size of the critical band as it varies with frequency.

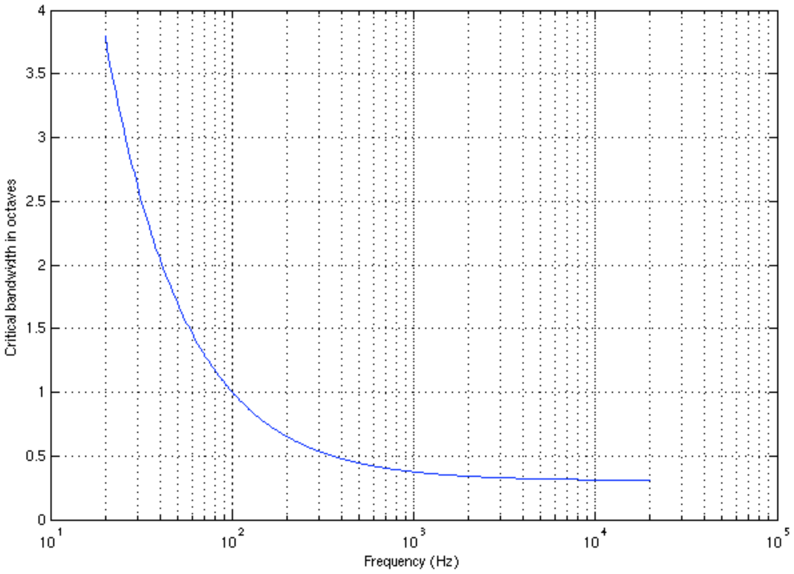

Figure 5 shows how the width of the critical band in octaves varies with frequency.

SmoothnessandPartials

PsycheLoui, 12 June 2006 (created 8 June 2006)

The video here demonstrates the interaction of two tones. The video shows two tones played at various intervals apart. Notice that when two pure tones are played at a seventh apart, they sound smooth; but when the two tones have several partials, they sound rough together.

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Now download the demo (Mac or Windows) and listen to tones at various intervals. The demo lets you manipulate the spectral content of these tones. Using spectra containing only odd harmonics (which approximate the frequency content of clarinets and flutes), play the tones in a continuous frequency spectrum.

The smoothness of a complex sonority is dependent to some degree on the number and configuration of the partials. Two pure tones are perceived as relatively smooth when they are not within a critical bandwidth of each other. As the number of partials increases, however, the percept can increase in roughness. This is because while the fundamental frequencies fall within distinct critical bands, the partials of each complex tone may interact.

Nonmusicians tend to rate pure tone 7ths as being close to an octave whereas musicians tend to think of pure tone 7ths as dissonant, similar to complex tone 7ths. This suggests that our pre-existing knowledge and expectation of the music, or top-down understanding, play a role in the perception of roughness.

Additivity of roughness

We have seen how roughness works for sonorities consisting of only two pitches---diads---but what about more complex sonorities? In many cases, a reasonable estimate of the roughness in a sonority can be found by summing the amount of roughness found in each band of the auditory filter across all bands as follows:

$$\rho = \sum_i \rho_i$$

Where r is roughness and ri is the roughness in each critical band. Figure 1 gives the output of the formula for two different orchestrations of the opening harmony of the third movement of Arnold Schoenberg's *Fünf Orchesterstüke* (Op. 16, "Farben") and a third version "orchestrated" with sinusoids.

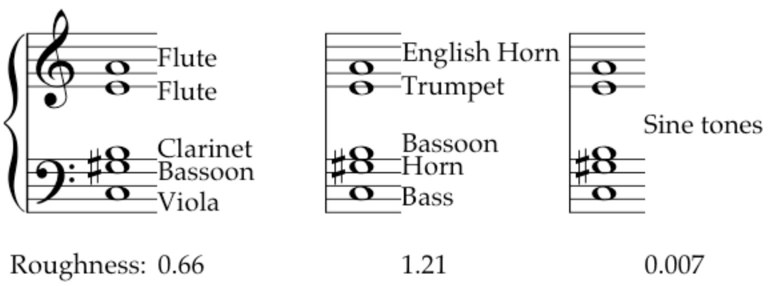

Figure 1: Roughness measurements for three orchestrations of Schoenberg's "Farben" chord.

orch. 1
orch. 2
orch. 3 (sinusoids)

In some cases, however, clusters of dissonant intervals will actually be perceived as smooth. An interesting example of this comes from the beginning of György Ligeti's *Atmospheres* which opens with a massive cluster of minor seconds spanning the lowest to highest registers. Although intuitively we might think that this sonority ought to sound highly dissonant, in fact it is quite smooth. This may be due to a smoothing of the amplitude modulation caused by phase cancellation. The first plot in figure 1 shows the waveform of two sinusoids at 440.0Hz and 466.1638Hz (a minor second), and the second plot shows the sum of 40 sinusoids at random frequencies between 440.0Hz and 466.1638Hz with random phases. The bottom two plots are closeups of the first two and show clearly the kind of smoothing of the amplitude fluctuations that contributes to the attenuation of roughness.

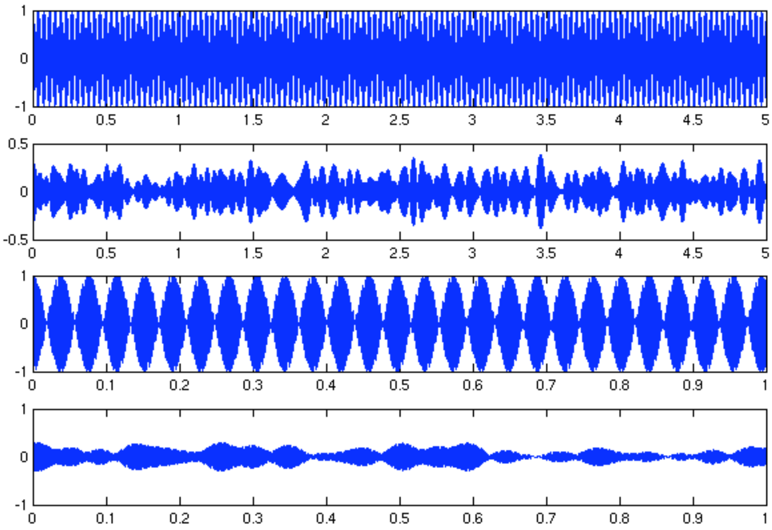

Figure 2a: sum of two sinusoids at 440.0Hz and 466.1638Hz (a minor second).
Figure 2b: sum of 40 sinusoids at random frequencies between 440.0Hz and 466.1638Hz with random phases.
Figure 2c: closeup of Plot 1.
Figure 2d: closeup of Plot 2.

Beating between 440 annd 466 Hz.

Smooth cluster of 40 sinusoids between 440 and 466 Hz.

Atmospheres

Frequency Selection, Tuning, and Orchestration

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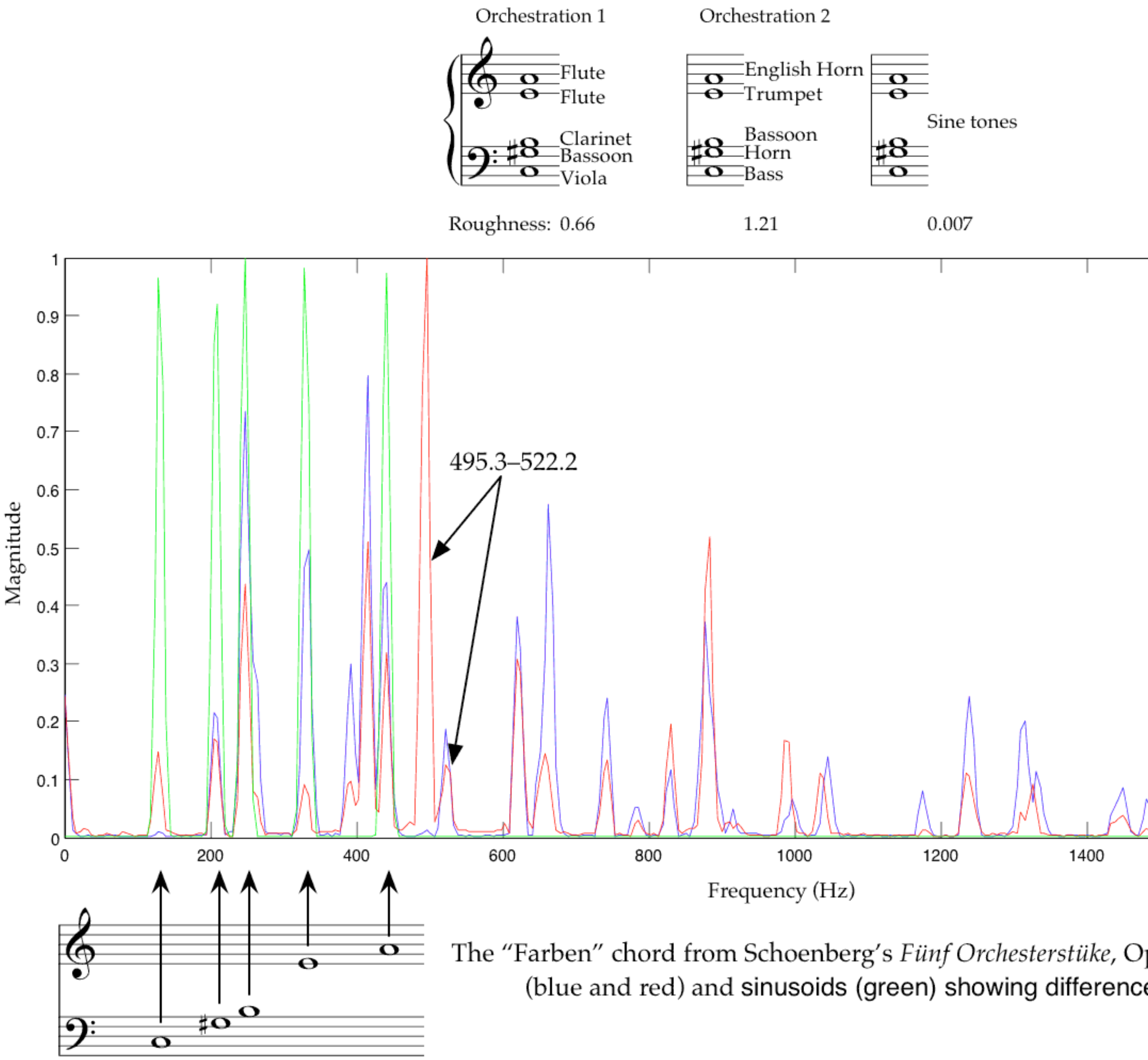
Throughout history, composers have known intuitively that orchestration plays a key role in the way a sonority is perceived, e.g. a dissonant chord can be smoothed a little by orchestrating it with strings or made maximally dissonant by orchestrating it with brass. An interesting example of this is opening sonority of the third movement of Arnold Schoenberg's *Fünf Orchesterstüke*, Op. 16. In the composition, the chord first appears orchestrated with two flutes, clarinet, bassoon, and viola and then with English horn, trumpet, bassoon, horn and bass. In figure 6, the spectra of the two orchestrations are plotted along with the sonority "orchestrated" using sine tones. The roughness values at the top of the figure, calculated with a modified version of Richard Parncutt's algorithm, conform to common orchestrational intuition, namely that the brighter instruments like the English horn and trumpet in the second orchestration will produce a more dissonant sonority, and that the sonority, when "orchestrated" with sinusoids, contains very little roughness since the smallest interval is only on the edge of a critical band.



James Tenney also employed psychoacoustic concepts of beating, amplitude modulation, and two-tone interaction in the orchestration of his 1988 piece *Critical Band*. (details to follow)

Hierarchy of intervals

Fig 8. In a psychoacoustical experiment where listeners made consonance ratings of sounds, Kameoka and Kuriyagawa (1969) demonstrated a hierarchy of intervals. Click here to download and run an experiment on rating the hierarchy of intervals.
Also see Northwestern University's demo here.
This diagram relates to tone profiles obtained from probe tone ratings (Krumhansl, 1990) which will be discussed at a later unit.

Consonance and Dissonance from the Top Down
As we discussed in an earlier unit, the experience of music is both a top-down and a bottom-up process. Our discussion of the auditory model to this point, including the AIM-MAT, has been exclusively a data-driven, bottom-up view of sound signal processing, but it is important to note that top-down effects are also heavily at work in the perception of sounds and music. Later in the unit we will discuss the perception of dissonance and consonance from the top down.

Counterpoint and the Wright-Bregman Hypothesis

PsycheLoui, 10 June 2006 (created 9 June 2006)

As sounds become increasingly separated into different streams (where streams can refer to spatial location in this case), beating diminishes and sound less rough. This explains why binaural beats do not sound as rough as monaural beats. Wright and Bregman [1] propose that certain auditory cues such as stream segregation can prevent the listener from hearing dissonant intervals as such. Figure 1 is an example taken from *Auditory Scene Analysis* ; in the top example, although the boxed intervals are dissonant, that dissonance is supressed by the strong separation of the two lines into separate streams. In the bottom example, the streaming cues are not present and the same intervals are heard as dissonant.

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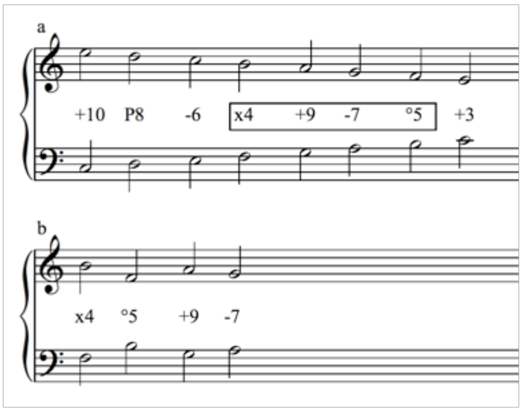

Figure 1: Strong segregation cues in the top example suppress the sensation of dissonance which is clearly heard in the bottom when those cues are removed.

The separation of sounds into streams is heavily influenced by top-down processes such as attention and long-term memory. Thus top-down influences on perception of consonance and dissonance begins to be important at this level. Referring back to Terhardt's two-component theory (Terhardt, 1977), factors contributing to musical consonance (as opposed to sensory consonance) include spatial localization, musical texture, and stream segregation, all of which are sensitive to top-down modulations.

David Huron (2001) has proposed that stream segregation and related perceptual principles give rise to our existing rules of counterpoint and voice-leading. Traditional voice-leading practices in this view include: the use of three to four distinct voices, the prominence of stepwise motion rather than leaps in each voice, and the avoidance of parallel fifths and octaves. These compositional practices may result from the perceptual principles of auditory streaming and source segregation. In order for each individual voice to be perceived as one stream, the perceptual principle of pitch proximity dictates the use of stepwise motion. Additionally, for distinct voices to be perceived as separable streams, frequency and amplitude comodulation are generally avoided, giving rise to the avoidance of parallel motion. These are only some of the ways in which compositional practices are governed by perceptual principles.

Other Factors Contributing to Roughness

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In addition to the interaction of two tones within close frequencies, some other factors that contribute to our perception of roughness include spatial location, phase-related fluctuations, and mistuning of consonant intervals.

Spatial location is important because it is a cue for the auditory system to compute the difference between input to the two ears. Although beats can arise monaurally from sounds mixing before they enter the ear, they can also arise neurally when sounds come together within the binaural system. The interaction of sounds presented binaurally results in **binaural beating**.

Phase-related fluctuation occurs when partials in a harmonic complex are not phase-locked. When the carriers of two amplitude-modulated tones are modulated in phase, the summated roughness is about twice that of either of the amplitude-modulated tones alone. Summated roughness is least when the modulations are anti-phase. Phase-locking is necessary for this to occur. (Terhardt, 2000)

Beating of mistuned consonances is another phenomenon related to the perception of roughness and beating. It is a reported phenomenon that beating is perceived when two simultaneously tones are played at frequencies that deviate very slightly from small-integer ratios. For example, a slightly mistuned octave will beat at the frequency at which the higher tone deviates from twice the lower tone; i.e. a 500Hz tone and a 1005Hz tone will beat at 5Hz (Viemeister et al., 2001). The origin of this phenomenon is unknown, but it is shown to be largely dependent upon the level and frequency of the lower component. Viemeister et al (2001) suggest that the perception of beating of mistuned consonances seems to be more dependent upon the fluctuations of the amplitude envelope of the two tones, rather than the fine temporal structure, or information within the amplitude envelope.

Neurobiology of Consonance and Dissonance

PsycheLoui, 9 June 2006 (created 9 June 2006)

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In order to further understand the different types of top-down modulation on consonance perception, it is important to understand the auditory pathway and the processes acting on the neural representations of sound. Such a detailed anatomical pathway is laid out in another unit, but the present discussion will focus on the stages of the auditory pathway specifically related to consonance and dissonance perception.

Neural coding of dissonance seems to begin at the level of the auditory nerve. Tramo et al. (2001) report that the temporal fluctuations of the auditory nerve firing pattern are inversely correlated with consonance perception. Thus it seems that the auditory nerve is passing on dissonance-related information towards further levels of the auditory system.

The Inferior Colliculus (IC) is a structure in the midbrain that plays an important role in dissonance perception. In studies involving single-unit recordings in the anesthetized cat, McKinney et al. (2003) have shown that neural firings of the IC correlate positively with amplitude modulation at the beat frequencies resulting from the interaction of two tones. Firings at the beat frequency were observed in the IC in response to simultaneously-presented minor 2nd tones for both pure and complex tones. IC firings also correlated with complex tones presented at a tritone apart (see Fig. 1). These findings suggest that the biological basis of dissonance between complex tones is coded at the midbrain level.

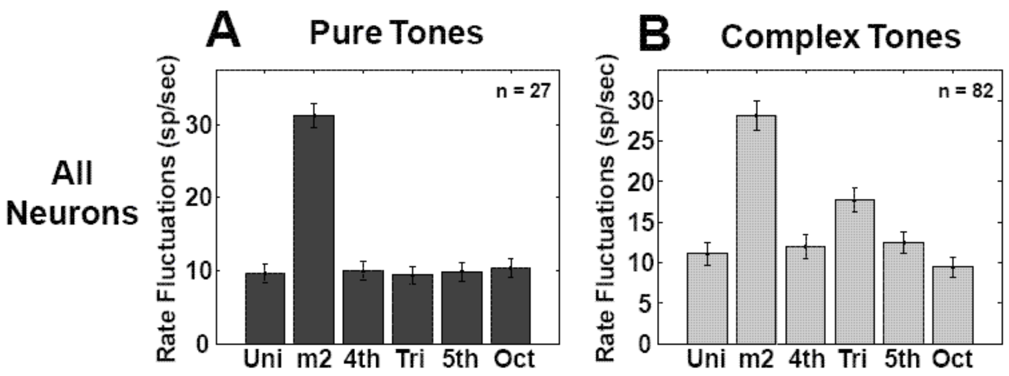

Fig. 1.Mean rates of fluctuations of IC neurons in response to pure and complex tone pairs.

Studies with lesion patients have also shown effects of consonance and dissonance at the level of the auditory cortex. Tramo et al. (2001) tested patients with bilateral A1 lesions and found that pitch perception and consonance perception were both impaired, but dissonance perception was intact. This led to their suggestion that consonance is an emergent property of the relationship between pitches of simultaneously-perceived tones, whereas dissonance is a function of roughness and beating which is independent of consonance.

SumMary

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In this unit we covered the many aspects of interactions between pure and complex sounds. Key concepts covered include:

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- auditory filter
- critical bandwidth
- roughness
- beating
- beat frequency
- hierarchy of intervals
- additivity of roughness
- timbre and orchestration

We have shown that the perception of consonance and dissonance results from both top-down and bottom-up perspectives.

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LinksnDownloads

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- Wikipedia article on consonance and dissonance
- Ohio State University's bibliography on sensory and musical consonance and dissonance
- Terhardt's website on auditory roughness
- The Cambridge AIM-MAT model

QuizItems

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1. Define the auditory filter. What is the relationship between critical band and the Gammatone filter?
2. Which of the following sounds most dissonant?
   a. C4 and B4 played on pure tones.
   b. C4 and B4 played on two clarinets on the opposite sides of a stage.
   c. C4 and B4 played on two trumpets on the same side of a stage.
   d. C4 and E4 played on two clarinets on the same side of a stage.
3. Under what conditions are binaural beats most likely to be perceived?
4. Calculate the beat frequency of the second partials (F_2) of complex tones with fundamentals at 440Hz and 441Hz respectively.
5. How does the Inferior Colliculus differentially encode pure tones and complex tones presented at a tritone apart?
6. According to the Wright-Bregman hypothesis, what factors may influence the perception of dissonance?