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THE TONE HEIGHT OF MULTI-HARMONIC TONES

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In the traditional representation, musical pitch is a helix – a single valued function existing in three space, much like a stretched coil spring (see Ueda & Ohgushi, 1987 for a review). The pitch helix has a circular dimension, referred to as "tone chroma", and a vertical dmension referred to as "tone-height", and pitch rises one octave per revolution of the circular dimension. This representation of pitch is supported by the perception of pure tones; in this case the only continuous path from a note to its octave is along the helix through all of the intervening tone-chroma values. For any given chroma value, say C, tone-height is a discrete variable, namely the set of octaves CO, Cl, C2 ... C8.

In the case of multi-harmonic tones, it is possible to move continuously from a note towards its octave without changing chroma. For example, consider the complex sound composed of all harmonics of 100 Hz starting in cosine phase (i.e. a pulse train), and the perceptual change that occurs when the odd harmonics are attenuated as a group. As the attenuation increases from 0 to 10 dB tone-height rises smoothly from the original octave (100 Hz) to the final octave (200 Hz) and there is no change in tone-chroma during this transition. This indicates that the domain of pitch for musical notes is more like the surface of the space enclosed by the pitch helix rather than a helical wire.

There are at least three ways of modifying a pulse train and producing sets of waves that all have the same tone-chroma but which sound "higher" or "lower" than the starting pulse train. This paper presents an experiment in which listeners judged the tone height of a large collection of these sounds. The experiments show that waves with the same period can produce tone-height judgments that consistently differ by more than an octave.

I MODIFYING TONE-HEIGHT WITHOUT CHANGING THE FUNDAMENTAL

The starting point for all of the manipulations in the current experiment was the multi-harmonic tone whose long term power spectrum is shown in Figure 1. The tone is a modified pulse train. Specifically, it is a set of 24 harmonics of a fundamental that ranged from 32 to 1,024 Hz in octave steps. The level of the components was reduced 3 dB/octave in an effort to balance the loudness in different conditions. All of the harmonics are in cosine phase, and so this stimulus is referred to as a "cosine-phase", or CPH sound.

A. Attenuation of the Odd or Even Harmonics: The first method of altering tone-height involves reducing the amplitude of either the odd harmonics or the even harmonics of the CPH sound. The effect of removing the odd harmonics has already been described; as the attenuation increases from 0 to 10 dB, tone-height rises an octave. Perceptually, the mid-point between the two octaves occurs when the odd harmonics are attenuated by 4-5 dB. Note, that when the attenuation is as much as 10 dB, the period of the wave is still clearly 10 ms. Alternately, the even harmonics can be attenuated leaving the odd harmonics stronger. In the extreme, like the previous manipulation, this doubles the component spacing in the spectrum. Unlike the previous manipulation, however, it does not double the fundamental which remains fixed at 100 Hz for all attenuations. Even-harmonic sounds are just CPH sounds an octave higher, and so their tone height is entirely predictable. The experiment contrasted CPH and odd-harmonic sounds, referred to as Odd-CPH sounds.

B. Shifting the Phase of the Odd or Even Harmonics: The second method of altering tone-height involves shifting the phase of all of the odd harmonics of the CPH stimulus, or all of the even harmonics of the CPH stimulus without changing their amplitudes. This produces what is referred to as "alternating phase", or APH sounds. All of the stimuli in the set have the identical period and the identical long-term power spectrum. When the phase change is sufficiently large (40° for a moderate level stimulus with a fundamental of 100Hz) it produces a change in the timbre of the sound. Patterson (1987) studied this phenomenon and, contrary to the predictions of Place Theory, the effect exists over a wide range of stimulus conditions that are relevant to music. Although it is not discussed in that paper, the APH stimuli sound "higher" than the corresponding CPH stimuli. Accordingly, the "Odd-APH" and "Even-APH" stimuli were compared with each other and the CPH sounds.

C. Reducing the Lower or Upper Harmonics by Filtering: The final method of manipulating tone-height without changing the period of the wave involves filtering out either the lower or upper harmonics of the CPH and APH sounds. When the lower harmonics are removed, the resulting sound is perceived to be "higher" than the original. In one case, the unresolved harmonics were removed, leaving harmonics 1-7- in the other case the resolved harmonics were removed, leaving harmonics 8-24. The former are referred to as "lower-harmonic sounds" (L) and the latter as "upper-harmonic sounds" (U). The unfiltered sounds bear the suffix (LU) for "lower and upper".

The filtering process was applied to all four of the previous stimulus types, CPH, Odd-CPH, Odd-APH and Even-APH, and so there were twelve stimulus conditions in the experiment. For convenience, the stimulus types are referred to as "instruments". Each of the instruments was presented at each of the octaves. Finally, for comparison, a thirteenth instrument, in the form of a sine tone, was included.

II EXPERIMENTAL PROCEDURE

When periodic sounds contain resolved harmonics, the auditory system has the option of two modes of analysis, typically referred to as the 'analytic' mode and the 'synthetic' mode. In the analytic mode the focus is on individual, resolved components and changes in those components from sound to sound. In the synthetic mode, the system focuses on the complete auditory image produced by the set of components as a whole. The latter mode is more common in music perception and in the natural environment generally. In order to promote this synthetic mode of perception, the individual trials of the experiment were constructed to give the impression of a tonal melody at the end of a musical phrase. Rhythmically, this sub-phrase was a triplet followed by three half notes. Melodically, each trial was restricted to the tonic plus the note above it and below it on the diatonic scale, for example, C with the B immediately below it and the D immediately above it. The triplet which initiated the trial was chosen at random from the notes B and D with the restriction that the triplet not be entirely B's or entirely D's. The three half notes were all C's. The fast moving triplet encourages synthetic listening and provides information about the instrument and the octave for the current trial. The three C's provide long clear notes (500 ms) for the listeners to make their octave judgments. On each trial the instrument/octave combination was chosen at random (without replacement) from the full set of sounds. There were four replications in the experiment and there were four listeners.

The listeners' task was simply to listen to the melody on each trial and then write down a number between one and six to indicate the octave of the three final C's. All of the listeners had musical experience but none was a professional musician. All of the listeners found the task easy to perform and they all produced the same pattern of results. For brevity, then, the results will be restricted to average data.

III RESULTS AND DISCUSSION

The data take the form of confusion matrices with the physical octave (i.e. the true period of the wave) on the abscissa and the average response of the four listeners on the ordinate, (for example, see Figure 1). If the listeners were invariably correct in identifying the physical octave, the data would all fall on the diagonal as shown by the dashed line. The data for individual instruments were surprisingly linear. Thus, it seemed reasonable to summarize the data in the form of regression lines, and it is these regression lines that appear in the figures.

A. The Effects of Physical Octave and Spectral Filtering: The two largest effects in the data are, not surprisingly, associated with the period of the stimulus wave and the position of the components in the spectrum. The regression line for the grand mean of all of the instruments has a slope slightly less than the diagonal and crosses the diagonal between octaves three and four. The slope reduction is largely attributable to the fact that the listeners responses were restricted to the range 1-6. This grand regression line indicates that the octave of these sounds is readily identifiable and that the primary determinant of tone height is the period of the wave or, alternately, the fundamental of the harmonic series.

The average response for all of the upper-harmonic instruments (U) is shown by the upper line in Figure 1. The lower pair of lines show the average data for all of the lower-harmonic instruments (L), and for all of the instruments that contained both lower and upper harmonics (LU). The data show that the spectral composition of the sound has a strong effect on tone height -- the upper harmonics on their own are perceived to be an octave above their physical octave when the period is largest, (octave 1) and still half an octave above their physical octave when the period is smallest (octave 6). Note, however, that it is not the spectral centre of gravity that determines tone height; removing harmonics 8 through 24 from the stimulus that has all harmonics does not change tone height. This indicates that tone height is largely determined by the lower harmonics in the stimulus.

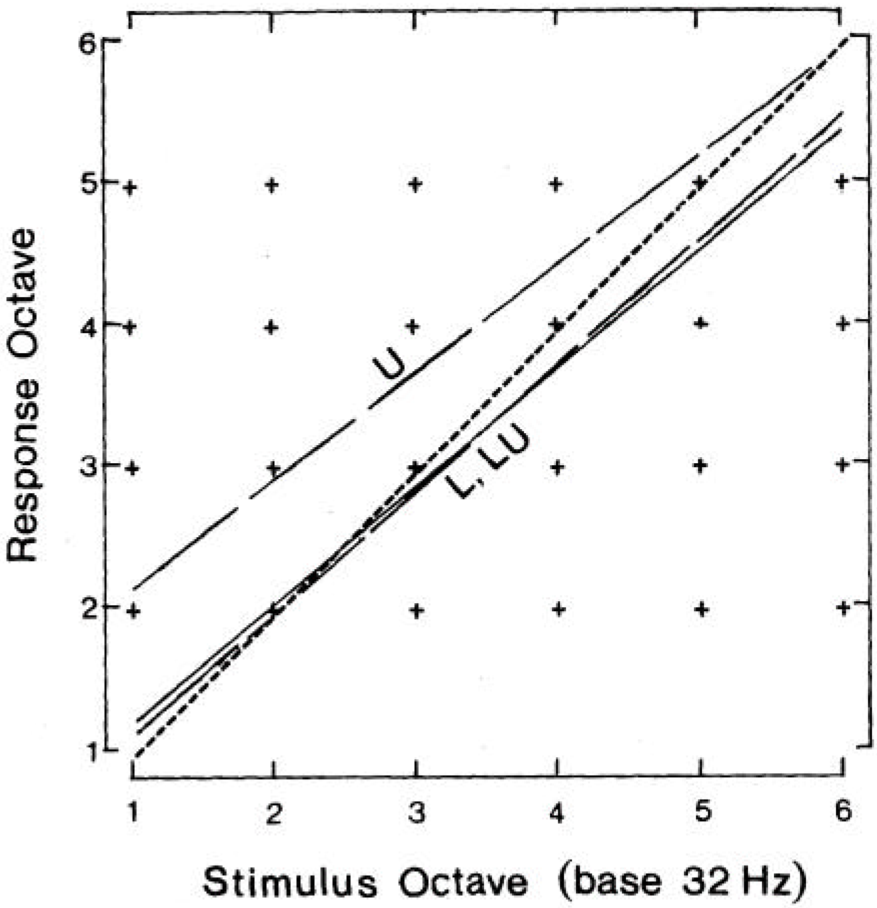

Figure 1. Perceived Octave as a function of Physical Octave for instruments containing harmonics 1-7 (L), harmonics 8-24 (U) and harmonics 1-24 (LU). When the lower harmonics are removed tone-height rises 0.5-1.0 octave.

B. The Effects of Harmonic Attenuation and Phase Shifting: The attenuation of the even harmonics of the CPH sound and the shifting of the phase of the even or odd harmonics do not produce main effects in this experiment, rather their effects are seen in interactions. The set of regression lines in Figure 2 is intended to illustrate these remaining interactive effects. The upper pair of broken lines show all of the data for the upper-harmonic instruments (U). Comparison of the broken lines shows

instruments with phase shifts sound higher than CPH instruments for notes in the lower half of the keyboard.

The data from seven of the nine remaining instruments fall essentially along the same regression line which is shown in the figure by the broad solid line. This occurs whenever the sound contains the lower harmonics and the even harmonics are present (i.e. not attenuated). In this case the presence or absence of the higher harmonics does not affect tone height. The tone height of the sine wave falls consistently below the main block of instruments for notes in the lower half of the keyboard. The final instrument Odd-CPH(L) produces a reliable reduction in tone height, similar in size o that associated with the sine tone, which further emphasizes the importance of the lower harmonics to tone height.

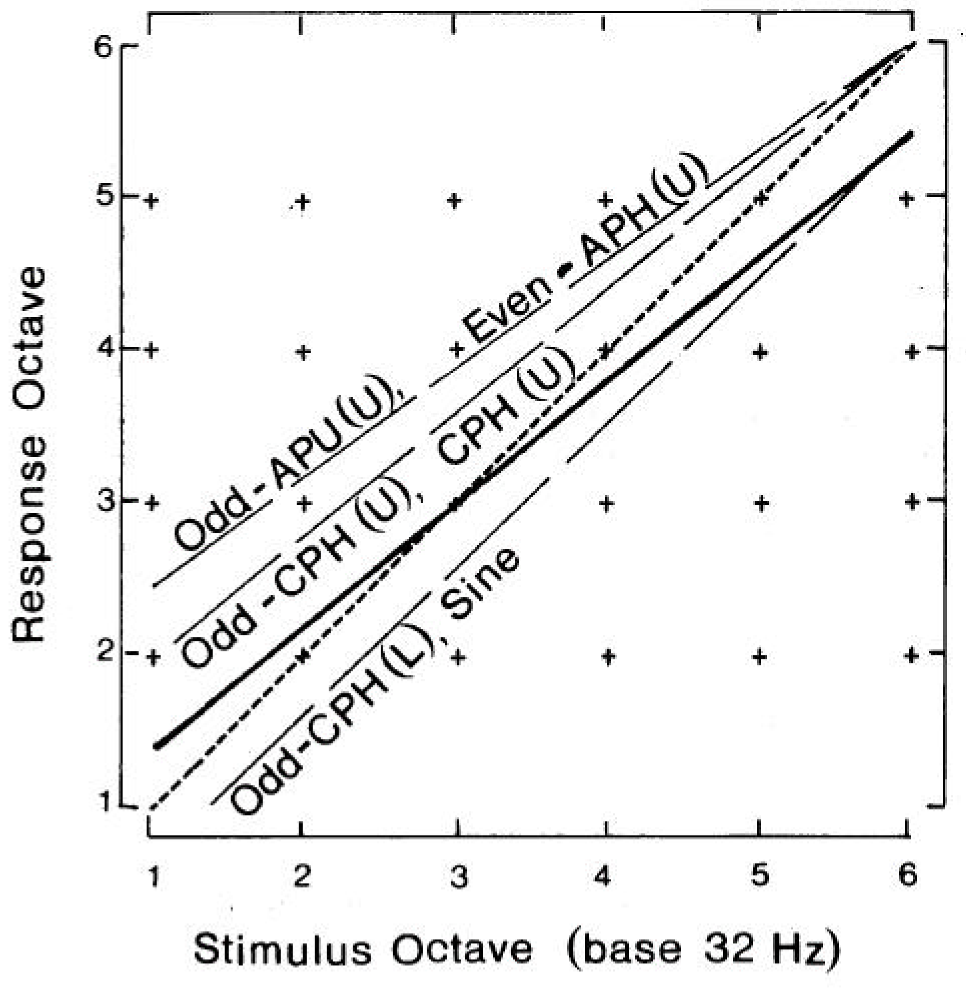

Figure 2. Perceived Octave as a function of Physical octave for all 13 instruments. Those not explicitly labeled are coincident with the bold regression line.

IV CONCLUSIONS

The regression lines in Figures 1 and 2 lead to the following general conclusions:

1. The tone height of multi-harmonic tones is readily apparent to listeners and the primary determinant of tone height is the period of the wave or, alternately, the fundamental of the harmonic series.

2. For a given period, tone height is primarily determined by the position of the lower harmonics, rather than the spectral centre of gravity of the stimulus. The sine tone on its own produces the lowest tone height judgments, but they are not significantly lower than those produced by the odd, resolved harmonics (1,3,5,and 7).

3. When the lower harmonics are removed, shifting the phase of alternate harmonics produces a significant increase in tone height.

4. All of the effects diminish as physical octave increases. The phase effect and the attenuation effect are limited to notes in the lower half of the keyboard.

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