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The Semitone Paradox

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This article concerns a pattern of tones that provides a curious exception to the principle of equivalence under transposition. When the pattern is transposed by a half octave, the identical pitches are heard but they appear to be reversed in time. Further, the pattern in any one key is heard quite differently by different listeners. The implications of this new pitch paradox are discussed.

As a general rule, musical patterns retain their perceptual identities when they are transposed to different keys. The phenomenon of perceptual equivalence under transposition can be readily illustrated by mapping log frequency into one dimension of visual space and time into another. As an example, Figure 1 shows a pattern consisting of two chords, presented in original form on the left, and transposed up six semitones on the right. It can be seen that the same shape emerges in the two visual representations: In both cases the higher tone moves one semitone up, and the lower tone moves one semitone down.

A second perceptual equivalence effect is based on the octave relation (Babbitt, 1960, 1965; Demany & Armand, 1984; Deutsch, 1969, 1973; Forte, 1973; Humphreys, 1939; Shepard, 1964, 1982; Ward & Burns, 1982; Westergaard, 1975, although see also Deutsch, 1972). The strong perceptual similarity between tones that are separated by octaves is acknowledged by the system of notation for the traditional musical scale. Here, tones that are related by octaves are given the same name and are held to be in the same pitch class. Thus tones C_3, C_4, and C_5 are held to be in pitch class C; tones $C\#_3$, $C\#_4$, and $C\#_5$ are held to be in pitch class C#; and so on.

Based on the foregoing considerations, we may regard pitch as consisting of two separable dimensions. The monotonic dimension of height defines its position on a continuum extending from high to low, and the circular

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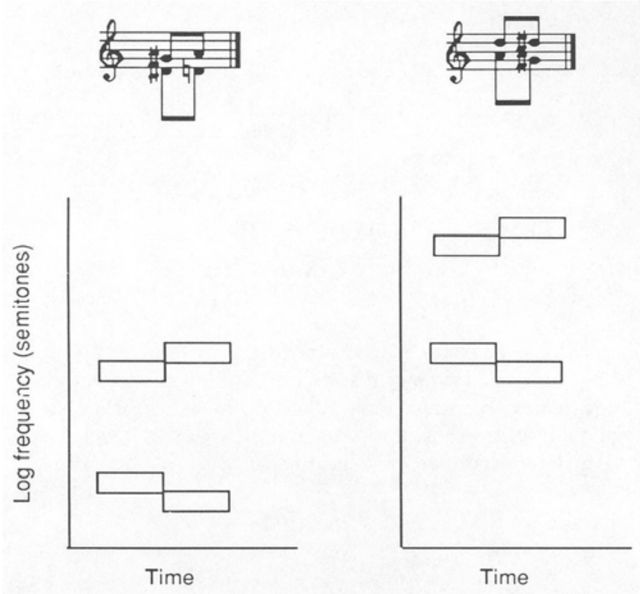

Fig. 1. A two-part pattern (G#—A/D#—D), presented in original form on the left and transposed up six semitones on the right. Such a pattern generally preserves its perceptual identity under transposition, just as the identical shape emerges in the two representations.

dimension of pitch class defines its position within the octave (Bachem, 1948; Charbonneau & Risset, 1973; Demany & Armand, 1984; Deutsch, 1969, 1973, 1982; Meyer, 1904; Nakajima, Tsumura, Matsuura, Minami, & Teranishi, 1988; Ohgushi, 1985; Revesz, 1913; Risset, 1971, Ruckmick, 1929; Shepard, 1964, 1965, 1982; Ueda & Ohgushi, 1987; and Ward & Burns, 1982).

In the past, it has been assumed that the dimensions of pitch class and height are orthogonal. In other words, statements such as "A is higher than D#" were considered meaningful only if octaves were also specified. (A_4 is higher than $D\#_4$, but lower than $D\#_5$). However, recent studies by the author and co-workers have uncovered situations in which orthogonality does not hold: For certain stimulus patterns the perceived heights of tones were found to vary systematically as a function of their positions along the pitch class circle (Deutsch, 1986, 1987, Deutsch, Moore, & Dolson, 1984, 1986; Deutsch, Kuyper, & Fisher, 1987).

The tones used in these studies were composed of octave-related sinusoids, which were generated under bell-shaped spectral envelopes. Such tones are heard as well-defined in terms of pitch class, but somewhat ambiguously in terms of height (Shepard, 1964; Risset, 1971). In one series of experiments, sequential pairs of tones were presented whose components were related by a half octave (or tritone), and so were diametrically opposed along the pitch class circle. For example, E would be presented followed by A#, or F followed by B; and so on. Listeners judged whether these tone pairs formed ascending or descending series. It was found that judgments depended in a specific fashion on the pitch classes of the tones: Those in one region of the pitch class circle were heard as higher and those in the opposite region as lower. In consequence, such a tone pair would be heard as ascending when played in one key, but as descending when played in a different key. Further, the direction of the relationship between pitch class and perceived height was found to vary substantially across listeners. Thus such a tone pair when played in any one key would be heard as clearly ascending by some listeners and yet as clearly descending by others. This phenomenon has been termed the tritone paradox (Deutsch, 1986, 1987; Deutsch et al., 1987).

Another series of experiments examined the relationship between pitch class and perceived height in a two-part pattern (Deutsch et al., 1984, 1986). This consisted of six tones altogether, and it was played in two different keys. In C major, the pattern consisted of tones D—E—F, presented simultaneously with tones B—A—G. In F# major, it consisted of tones G#—A#—B, presented simultaneously with tones E#—D#—C#. Listeners generally organized the pattern as two melodic lines in accordance with pitch proximity, so that they heard one line that ascended by a minor third together with another that descended by a major third. However, depending on the key in which the pattern was presented, either the ascending line was heard as higher and the descending line as lower, or the descending line was heard as higher and the ascending line as lower. Thus when the pattern was transposed, the relative heights of the different pitch classes remained the same, which resulted in a perceived interchange of voices. Further, the pattern in any given key was heard with the ascending line as higher by some listeners but with the descending line as higher by others.

The two-part pattern just described was composed of melodic lines that encompassed relatively large regions of the pitch class circle. In consequence, listeners were free to focus on different pitch classes in making their judgments. As a result, the orientation of the pitch class circle with respect to height could be determined only broadly. The present study was undertaken to provide a more fine-grained analysis of the relationship between pitch class and perceived height for the case of simultaneous tones.

The basic pattern used in this study is illustrated in Figure 1. It consisted of two successively presented pairs of tones, which were diametrically oppossed along the pitch class circle. On one side of the circle, the second tone was a semitone higher than the first, and on the other side, the second tone was a semitone lower. Figure 2 presents an example of this pattern in terms of the positions of the tones along the pitch class circle.

In a preliminary study, it was found that listeners generally perceived this pattern as two stepwise lines that move in contrary motion.[1] For example,

1. Although most listeners perceive this pattern as two stepwise lines that move in contrary motion, a few listeners obtain ambiguous percepts. Such percepts are not examined in this article.

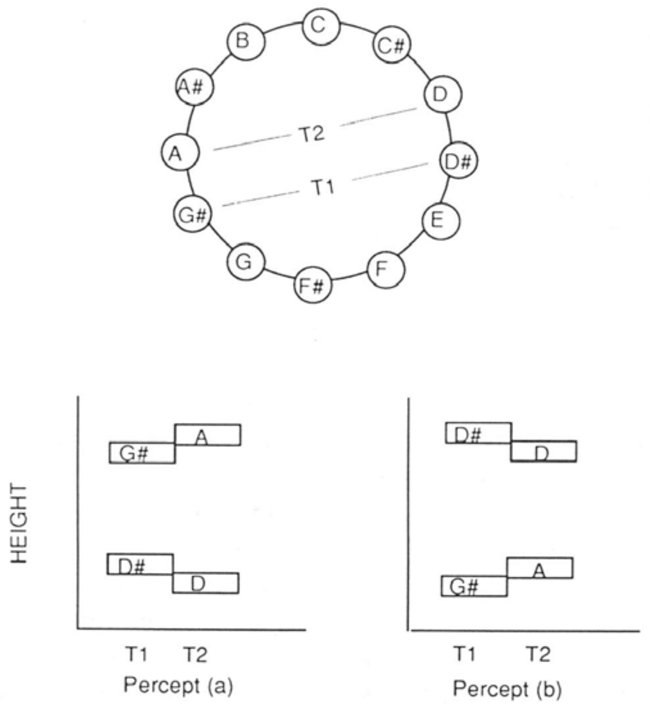

Fig. 2. Example of the stimulus pattern employed in the study, together with two alternative perceptual organizations. Tones G# and D# are simultaneously presented at T1, and tones A and D at T2. Listeners organize this pattern as two stepwise lines that move in contrary motion; that is, as the ascending line G#—A, together with the descending line D#—D. However, the ascending line is heard as higher by some listeners [as in percept (a)], but the descending line is heard as higher by others [as in percept (b)].

the pattern shown in Figure 2 was generally heard as the ascending line G#—A, played together with the descending line D#—D. However, some listeners heard the ascending line as higher and the descending line as lower, whereas others heard the descending line as higher and the ascending line as lower. These two alternative perceptual organizations are also shown in Figure 2. In the experiments to be described, subjects judged for each pattern whether the higher line ascended or descended, and from such judgments it was inferred which tones were heard as higher and which as lower. Thus in the case of the example in Figure 2, if the subject judged the higher line to be ascending, then it follows that he heard pitch classes G# and A as higher and D# and D as lower. If on the other hand he judged the higher line to be descending, then it follows that he heard pitch classes D# and D as higher and G# and A as lower.

In order to examine the possible influence of spectral factors on judgments, patterns were generated under envelopes that were centered at different positions along the spectrum. Altogether, 12 different envelopes were employed, with peaks spaced at 1/4 octave intervals. Thus the envelope peaks encompassed a three-octave range. The use of these envelopes enabled a partitioning of any possible effects of the relative amplitudes of the sinusoidal components of the tones from any possible effects of their overall heights.

Experiment 1

METHOD

Stimulus Patterns

Each tone was composed of six sinusoids that were separated by octaves, and their amplitudes were scaled by a fixed, bell-shaped spectral envelope. The following is the general form of the equation describing the envelope:

$$A(f) = 0.5 - .05\cos\left[\frac{2\pi}{\gamma}\log_{\beta}\left(\frac{f}{f_{\min}}\right)\right] \qquad f_{\min} \le f \le \beta^{\gamma} f_{\min}$$

where $A(f)$ is the relative amplitude of a given sinusoid at frequency fHz, β is the frequency ratio formed by adjacent sinusoids (so that for octave spacing, β = 2), γ is the number of β cycles that are spanned), and f_{min} is the minimum frequency for which the amplitude is non-zero. In this way, the maximum frequency for which the amplitude is non-zero is γβ cycles above $f_{min.}$ Throughout, the values β = 2 and γ = 6 were used, and as a result the spectral envelope always spanned exactly 6 octaves, from f_{min} to 64 f_{min}.

Each pattern was generated under envelopes that were placed at eight different positions along the spectrum, with peaks spaced exactly at 1/4 octave intervals, so encompassing a two-octave range. Figure 3 shows the four positions of the envelope within the higher octave, with peaks at C_5 (523 Hz, f_{min} = 65.4 Hz), D#$_5$ (622 Hz, f_{min} = 77.7 Hz), F#5 (740 Hz, f_{min} = 92.4 Hz), and A_5 (880 Hz, f_{min} = 110 Hz). Figure 4 shows its four positions within the lower octave, with peaks at C_4 (262 Hz, f_{min} = 32.7 Hz), D#$_4$ (311 Hz, f_{min} = 38.8 Hz), F#$_4$ (370 Hz, f_{min} = 46.2Hz), and A_4 (440 Hz, f_{min} = 55.0 Hz). We may note that the relative amplitudes of the sinusoidal components of tones generated under the C_5 envelope were identical to those of tones generated under the C_4 envelope. The same held for tones generated under the D#$_5$ and D#$_4$ envelopes, under the F#$_5$ and F#$_4$ envelopes, and under the A_5 and A_4 envelopes. These patterns of relationship thus enabled a partitioning of any effects of the overall heights of the tones from those of the relative amplitudes of their components.

Twelve patterns were generated under each of the eight spectral envelopes, corresponding to the pitch class combinations C—C#/G—F#, C#—D/G#—G,D—D#/A—G#, D#—E/A#—A, E—F/B—A#, F—F#/C—B, F#—G/C#— C, G#–C, G—G#/D—C#, G#—A/D#—D, A—A#/E—D#, A#—B/F—E, and B—C/F#—F. In this way, 96 patterns were generated altogether. These were presented in blocks of 12, with each block composed of patterns generated under one of the spectral envelopes and containing one example of each of the 12 pitch-class combinations. Within blocks, the patterns were presented in any of four orders. The orders were haphazard, with the restriction that the same pitch class did not occur in any two consecutive patterns.

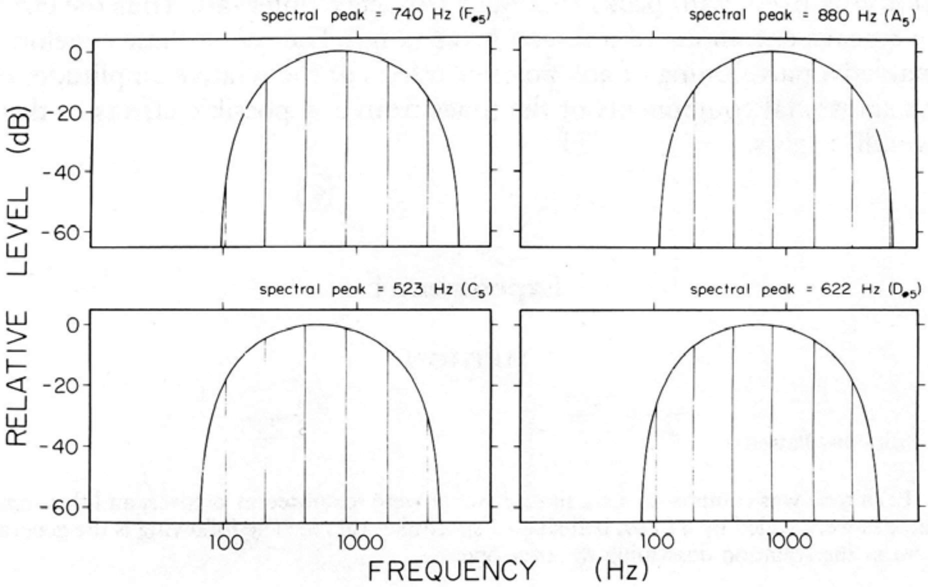

Fig. 3. Experiment 1. Representation of the spectral composition of tones of pitch class G#, generated under the four spectral envelopes centered in the higher octave.

Thus, 32 blocks were created altogether. These were presented in two sessions, with 16 blocks in each session. The entire procedure was repeated three times, so that each subject participated in six sessions.

Procedure

Subjects were tested in soundproof booths. On each trial one of the patterns was presented, and the subjects judged whether the higher line formed an ascending or a descending series. All tones were 500 msec in duration, and there were no gaps between tones within a pattern. Trials within blocks were separated by 5-sec pauses, during which the subjects made their judgments. Blocks were separated by 1-min pauses. There was a break of 5 min between the eighth and ninth blocks. A few warm-up trials were administered at the beginning of each session.

Equipment

Tones were generated on a VAX 11/780 computer, interfaced with a DSC-200 Audio Data Conversion System, and using the cmusic sound synthesis software (Moore, 1982). They were recorded and played back on a Sony PCM-F1 digital audio processor, the output of which was passed through a Crown amplifier and presented to subjects binaurally through headphones (Grason-Stadler TDH-49), at an approximate level of 72 dB SPL.

Subjects

Four subjects with normal hearing participated in the experiment, and they were paid for their services. All subjects heard the pattern consistently as two stepwise lines that moved

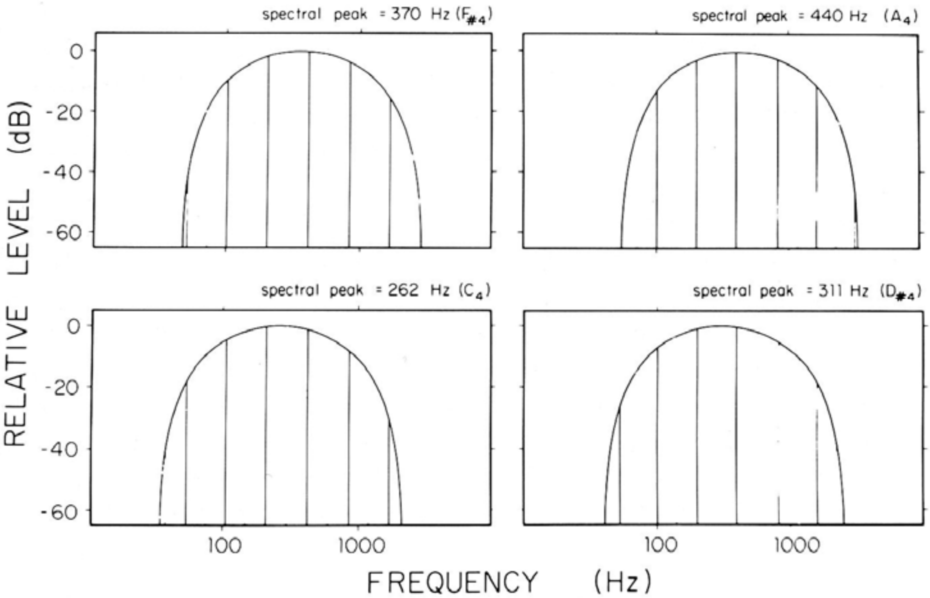

Fig. 4. Experiment 1. Representation of the spectral composition of tones of pitch class G#, generated under the four spectral envelopes centered in the lower octave.

in contrary motion. This was documented both by their verbal descriptions and also by their informal notations of the pattern. Two subjects (T.K. and M.F.) were graduate students in the Music Department at the University of California, San Diego, and two (A.G. and K.D.) were undergraduates who had had no musical training. None of the subjects had absolute pitch, in the sense of being able to attach verbal labels to tones presented in isolation.

RESULTS

The percentages of judgments that the higher line formed an ascending series were plotted as a function of the pitch classes of the tones in the ascending line. Figure 5 displays the results for each subject separately, averaged over the four envelopes centered in the higher octave (i.e., at C_5, $D\#_5$, $F\#_5$, and A_5), and also averaged over the four envelopes centered in the lower octave (i. e., at C_4, $D\#_4$, $F\#_4$, and A_4). As can readily be seen, the judgments of each subject depended in an orderly fashion on the positions of the tones along the pitch class circle, so that those in one region of the circle were heard as higher and those in the opposite region as lower. It can also be seen that the profiles relating pitch class to perceived height varied substantially across subjects. Further, for each subject, the profiles relating pitch class to perceived height were very similar for the higher and lower octaves.

Figure 6 displays the results for each subject separately, as a function of the pitch class of the peak of the spectral envelope, and so of the relative amplitudes of the sinusoidal components of the tones. (In other words, results were averaged over envelopes centered at C_4, and C_5, at D#$_4$ and D#$_5$, at F#$_4$ and F#$_5$, and at A_4 and A_5). It can be seen that, for each subject, the form of relationship between pitch class and perceived height was very similar across these variations in the relative amplitudes of the sinusoidal components.

For each subject, a four-way ANOVA was performed, with pitch class of the first tone of the ascending line (pitch class), octave of the peak of the spectral envelope (overall height), and pitch class of the peak of the spectral envelope (relative amplitude) as fixed factors, and replications as a random factor. For subject K.D., the main effect of pitch class was highly significant [F (11,22) = 249.45, $p < .001$]; no other main effects were significant (for overall height, [F (1,2) = 3.00, $p > .05$], for relative amplitude [$F < 1$]). The interaction between pitch class and overall height was marginally significant [F (11,22) = 2.63, $p < .05$]; the interaction between pitch class and

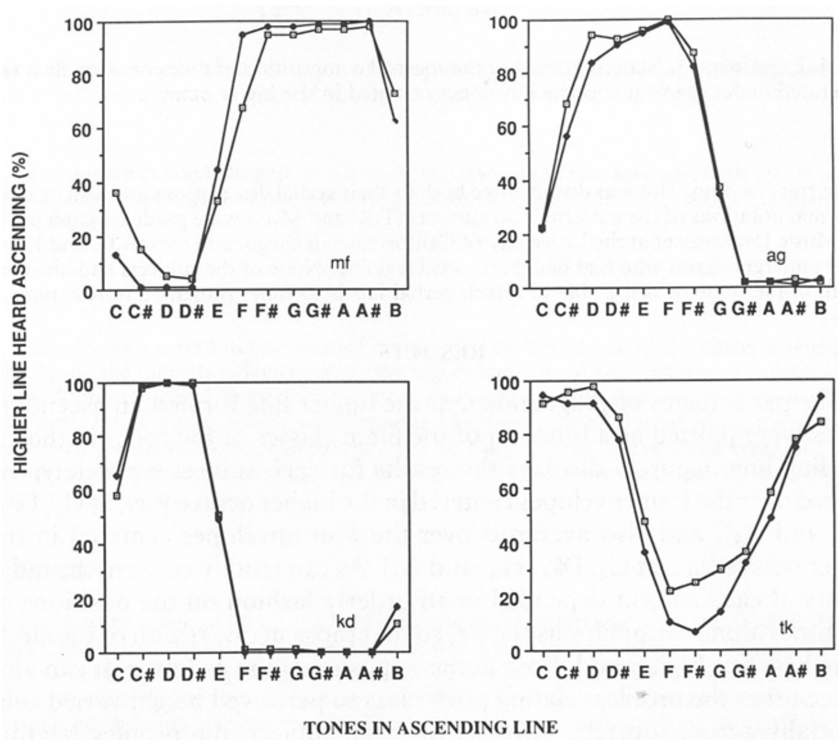

Fig. 5. Experiment 1. Percentages of judgments that the higher line formed an ascending series, plotted as a function of the pitch classes of the tones in the ascending line. Results are displayed for each subject separately, averaged over the four spectral envelopes centered in the higher octave; at C_5, D#$_5$, F#$_5$, and A_5, (⊡), and over the four spectral envelopes centered in the lower octave (at C_4, D#$_4$, F#$_4$, and A_4 (♦).

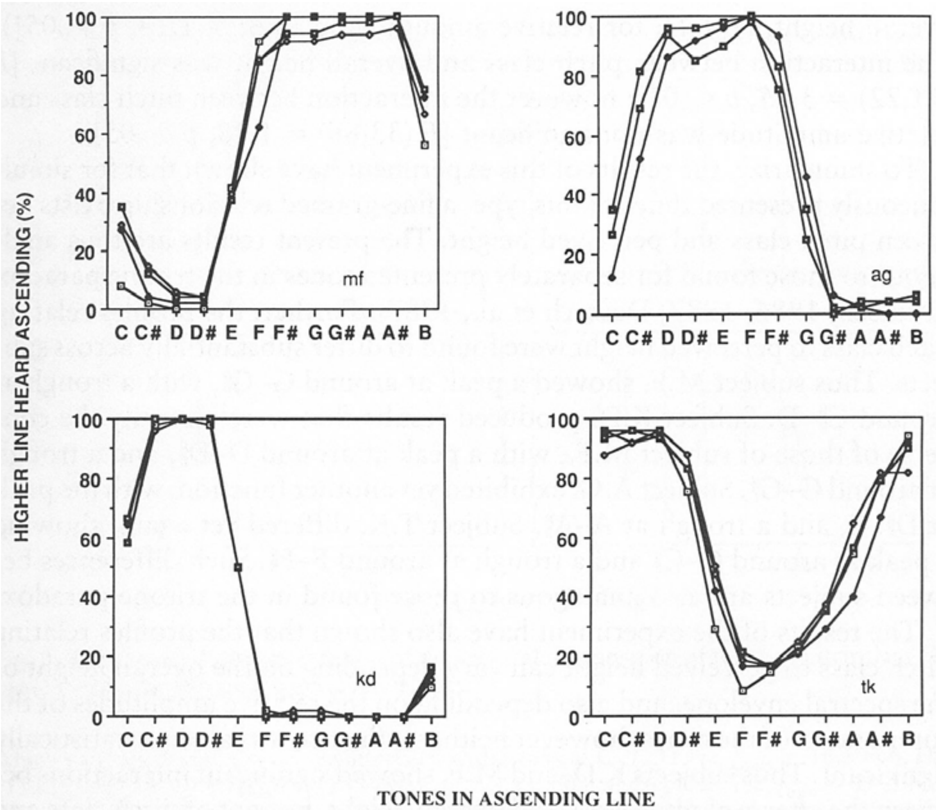

Fig. 6. Experiment 1. Percentages of judgments that the higher line formed an ascending series, plotted as a function of the pitch classes of the tones in the ascending line. Results are displayed for each subject separately, as a function of the relative amplitudes of the spectral components; that is, averaged over envelopes centered at C_4 and C_5(⊡), D$\#_4$, and D$\#_5$(♦) F$\#_4$ and F$\#_5$(□) and A_4 and A_5 (◇).

relative amplitude was nonsignificant [$F < 1$]. For subject T.K., the main effect of pitch class was highly significant [$F\ (11,22) = 11.57$, $p < .0001$]; no other main effects were significant (for overall height, [$F\ (1,2) = 2.81$, $p > .05$]; for relative amplitude, [$F\ (3,6) = 1.05$, $p > .05$). The interaction between pitch class and overall height was nonsignificant [$F\ (11,22) = 1.79$; $p > .05$]; the interaction between pitch class and relative amplitude was also nonsignificant [$F\ (33,66) = 1.11$; $p > .05$]. For Subject A.G., the main effect of pitch class was highly significant [$F\ (11,22) = 123.81$; $p > .0001$]; no other main effects were significant (for overall height, [$F\ (1,2) = 1.71$, $p > .05$]; for relative amplitude, [$F < 1$]). The interaction between pitch class and overall height was nonsignificant [$F\ (11,22) = 1.72$; $p > .05$]; the interaction between pitch class and relative amplitude was, however, highly significant [$F\ (33,66) = 3.70$; $p < .0001$]. For subject M.F., the main effect of pitch class was highly significant [F

(11,22) = 53.01, $p < .0001$]; no other main effects were significant (for overall height, [$F < 1$]; for relative amplitude, [F (3,6) = 1.14, $p > .05$]). The interaction between pitch class and overall height was significant [F (11,22) = 3.95, $p < .01$]; however the interaction between pitch class and relative amplitude was nonsignificant [F (33,66) = 1.48, $p > .05$].

To summarize, the results of this experiment have shown that for simultaneously presented tones of this type, a fine-grained relationship exists between pitch class and perceived height. The present results are thus analogous to those found for separately presented tones in the tritone paradox (Deutsch, 1986, 1987; Deutsch et al., 1987). Further, the profiles relating pitch class to perceived height were found to differ substantially across subjects. Thus subject M.F. showed a peak at around G—G#, with a trough at around C#—D. Subject K.D. produced results that were virtually the converse of those of subject M.F., with a peak at around D—D#, and a trough at around G—G#. Subject A. G. exhibited yet another function, with the peak at D#—E, and a trough at A—M. Subject T.K. differed yet again, showing a peak at around C—C# and a trough at around F—F#. Such differences between subjects are also analogous to those found in the tritone paradox.

The results of the experiment have also shown that the profiles relating pitch class to perceived height can vary depending on the overall height of the spectral envelope, and also depending on the relative amplitudes of the components of the tones; however neither influence was always statistically significant. Thus subjects K.D. and M.F. showed significant interactions between the effects of pitch class and overall height, but not of pitch class and relative amplitude. In contrast, subject A. G. showed a significant interaction between the effects of pitch class and relative amplitude but not between pitch class and overall height. Finally, subject T.K. showed no significant interaction with either factor. We should also note that even when significant interactions were obtained, the differences between the profiles relating pitch class to overall height were quite small.

Experiment 2

Experiment 1 demonstrated the presence of an orderly relationship between pitch class and perceived height, which was consistent over spectral envelopes whose positions varied over two octaves. Experiment *2* extended this investigation to the case of spectral envelopes whose positions varied over a third octave.

METHOD

The shape of the spectral envelope was identical to that used in Experiment 1. As illustrated in Figure 7, the envelope was placed at four different positions along the spectrum,

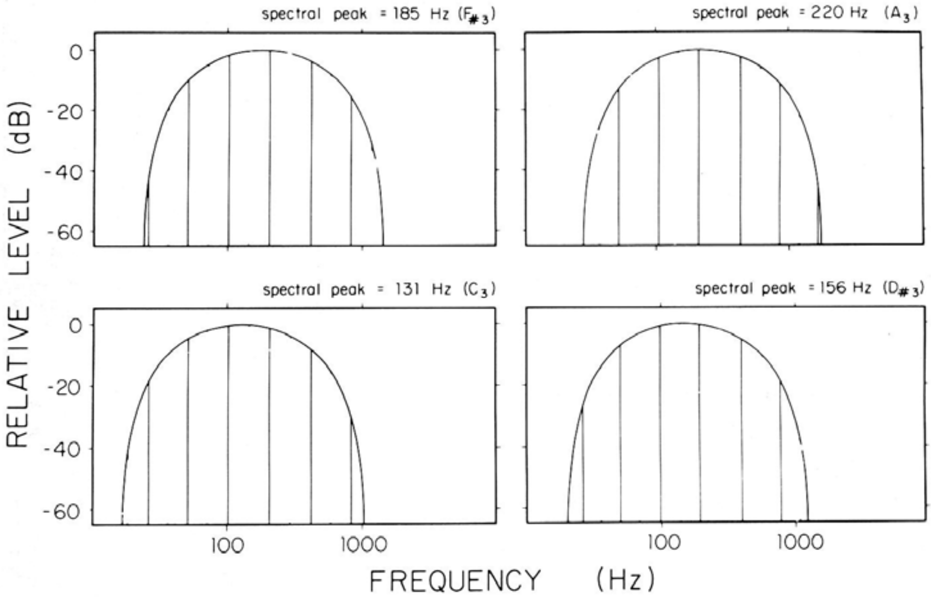

Fig. 7. Experiment 2. Representation of the spectral composition of tones of pitch class G#, generated under the four spectral envelopes.

which were spaced at 1/4-octave intervals, with peaks at C_3 (131 Hz, f_{min} = 16.3 Hz), D$\#_3$ (156 Hz, f_{min} = 19.4 Hz), F$\#_3$ (185 Hz, f_{min} = 23.1 Hz), and A_3 (220 Hz, f_{min} = 27.5 Hz). The relative amplitudes of the sinusoidal components of tones generated under the four envelopes were therefore identical to those in Experiment 1.

Twelve patterns were generated under each of the four envelopes. These corresponded to the pitch-class combinations C—C#/G—F#, C#–D/G#—G, ..., B—C/F#—F; as in Experiment 1. Forty-eight patterns were thus generated altogether. These were presented in blocks of 12, with each block consisting of patterns generated under one of the envelopes, and containing one example of each of the 12 pitch-class combinations. Within blocks, the combinations were presented in any of four orders. The orders were haphazard, with the restriction that the same pitch class did not occur in any two consecutive pairs. Sixteen blocks were thus created altogether, and these were presented in a single session. The entire procedure was repeated three times, so that each subject participated in three sessions. The methodology was otherwise identical to that in Experiment 1, and the same subjects were employed.

RESULTS

Figure 8 displays the results from each subject separately, for patterns generated under each of the four spectral envelopes (i.e., centered at C_3, D$\#_3$, F$\#_3$, and A_3). As can be seen, the profiles relating pitch class to perceived height were highly similar to those in Experiment 1. Large differences across subjects were again apparent, and again the profiles were quite similar across differences in the position of the spectral envelope.

A three-way ANOVA was performed on the data from each subject separately, with pitch class of the first tone of the ascending line (pitch class)

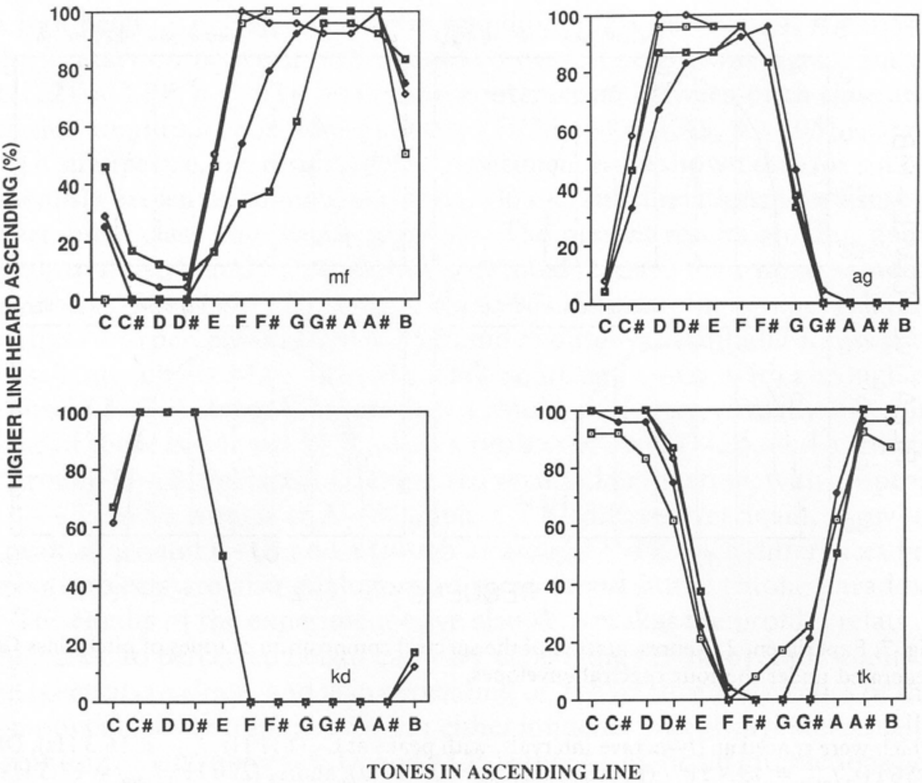

Fig. 8. Experiment 2. Percentages of judgments that the higher line formed an ascending series, plotted as a function of the pitch classes of the tones in the ascending line. Results are displayed for each subject separately, for patterns generated under each of the spectral envelopes, that is, centered at C_3 (⊡), D#$_3$ (♦), F#$_3$ (□), and A_3 (◇).

and position of spectral envelope (envelope position) as fixed factors, and replications as a random factor. For subject K.D., the main effect of pitch class was highly significant [$F(11,22) = 633.66$, $p < .0001$]; the main effect of envelope position was nonsignificant [$F < 1$]. The interaction between pitch class and envelope position was nonsignificant [$F < 1$]. For subject T.K., the main effect of pitch class was highly significant [$F\ (11,22) = 233.16$, $p < .0001$]; the main effect of envelope position was nonsignificant [$F<1$]. The interaction between pitch class and envelope position was highly significant [$F(33,66) = 2.99$, $p = .0001$]. For subject A.G., the main effect of pitch class was highly significant [$F\ (11,22) = 61.40$, $p < .0001$]; the main effect of envelope position was non-significant [$F\ (3,6) = 2.78$, $p > .05$]. The interaction between pitch class and envelope position was nonsignificant [$F\ (33,66) = 1.46$, $p > .05$]. For subject M.F., the main effect of pitch class was highly significant [F

(11,22) = 49.30, $p < .0001$]; the main effect of envelope position was non-significant [$F(3,6) = 3.62$, $p > .05$]. The interaction between pitch class and envelope position was highly significant [$F(33,66) = 5.45$, $p < .0001$].

The results of this experiment, when combined with those of Experiment 1, show that the profiles relating pitch class to perceived height derived from individual listeners are very similar across envelope positions which vary over a three-octave range. They also show, as in Experiment 1, that a significant influence of spectral factors is sometimes present, but not always so. In this experiment, a significant interaction between the effects of pitch class and spectral envelope position was obtained for subjects T.K. and M.F., but not for subjects A.G. or K.D.

General Discussion

The results of the present study have extended those of Deutsch, et al. (1984, 1986) in showing that the perceived heights of tones in two-part patterns can vary in a specific fashion depending on their positions along the pitch-class circle. In this respect, the findings are analogous to those of Deutsch (1986, 1987) and Deutsch et al. (1987) for sequential pairs of single tones, in which similarly fine-grained profiles were obtained. We may note that in this experiment the profiles derived from individual subjects were highly similar for spectral envelopes centered at four different positions within the octave. They could not, therefore, have been based on differences in the relative amplitudes of the sinusoidal components of the tones. Further, the profiles were highly similar for spectral envelopes whose positions varied across a three-octave range. They could not, therefore, have been based in any simple way on patterns of loudness or salience for the individual sinusoidal components. These profiles must therefore have reflected a basic influence of pitch class on perceived height.

The above findings lead to the remarkable consequence that transposing such a pattern may cause it to be heard as reversed in time. This is illustrated in Figure 9. The case is taken of pattern G#—A/D#—D, and a listener such as M.F. who obtains percept (a) in Figure 2 for this pattern, and so hears tones G# and A as higher and tones D# and D as lower. When untransposed, this listener hears the pattern as notated on the left of this figure, with the ascending line G#—A as higher and the descending line D#—D as lower. When the pattern is transposed by a half-octave, then G# interchanges with D, and A interchanges with D. However, since this listener continues to hear tones G# and A as higher and tones D# and D as lower, he now perceives the pattern as notated on the right of the figure, with the descending A—G# line as higher and the ascending D—D# line as lower! Transposing the

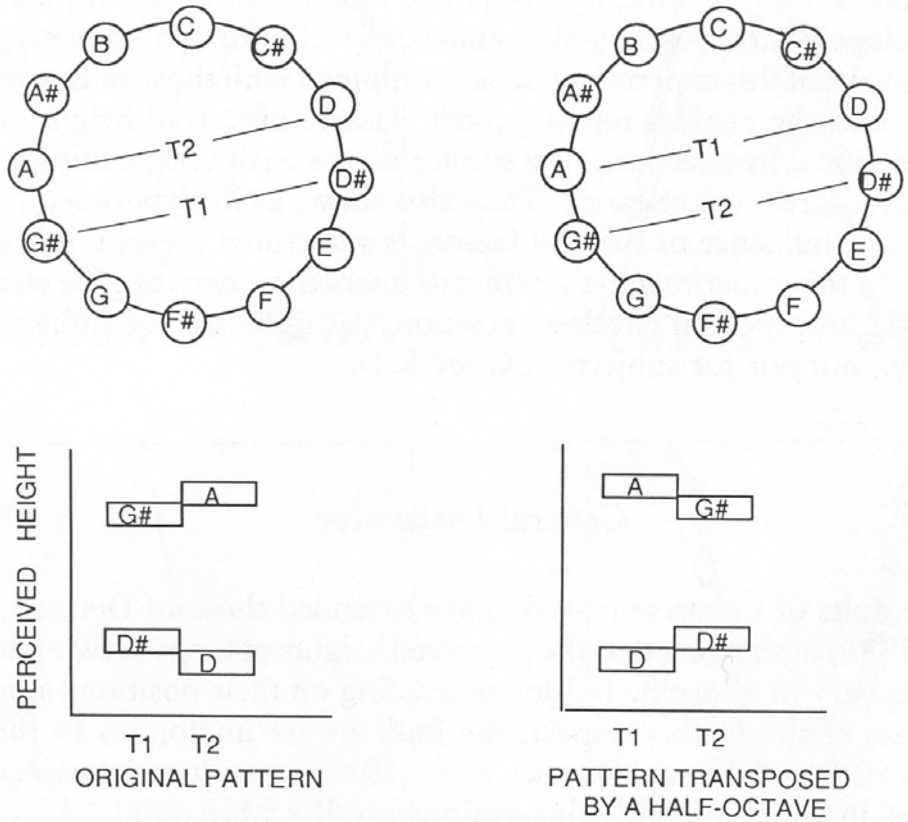

Fig. 9. Pattern G#—A/D#—D, presented in original form and transposed by six semitones, together with the percepts obtained by the listener such as in Figure 2a. Observe that the identical tones are heard, but as though reversed in time, which leads to a mirror-image representation in visual form.

pattern therefore results in an apparent reversal of the temporal order of the tones.

A particularly compelling demonstration of this paradox may be achieved by recording such a pattern on tape and then playing the tape back at different speeds. Specifically, if it is first played at normal speed, and is then sped up so that all the pitches are transposed by a half octave, the new pattern is heard as the retrograde of the original.

This striking demonstration is related to another that can be generated with the pattern giving rise to the tritone paradox (Deutsch, 1986). For example, we may take the case of a listener who hears pitch class A as higher and D# as lower, and consider the tone pair D#—A. When played at normal speed, the listener hears this tone pair as the ascending line D#—A. When the tape speed is increased so that the pitches are transposed up a half octave, the listener now hears the identical tone pair as the descending line A—D# instead. In the case of the tritone paradox, then, speeding up the tape by a half octave produces, in addition to a temporal reversal, an apparent inversion of the pattern. In the case of the semitone paradox described here, the same procedure results in a temporal reversal alone. Both these paradoxes represent violations of the principle of equivalence under transposition, which, as described earlier, is considered one of the fundamental characteristics of music perception.

Another remarkable aspect of these findings concerns the substantial differences between listeners in the direction of the relationship between pitch class and perceived height. As a result of these differences, extended passages formed of such patterns will be heard by listeners in radically different ways. This may be illustrated for the case of subjects M.F. and K.D. and for patterns generated under the spectral envelope centered at C_5. As shown in Figure 10, the pattern G#/C#—G/D, F#/C#—G/C, A/D—G#/D# is heard by subject M.F. as notated on the upper staff, but by subject K.D. as notated on the lower staff instead! We may hypothesise that such perceptual differences might occur in listening to natural music also, for example, in multivoiced orchestral contexts. This interesting possibility remains to be explored.

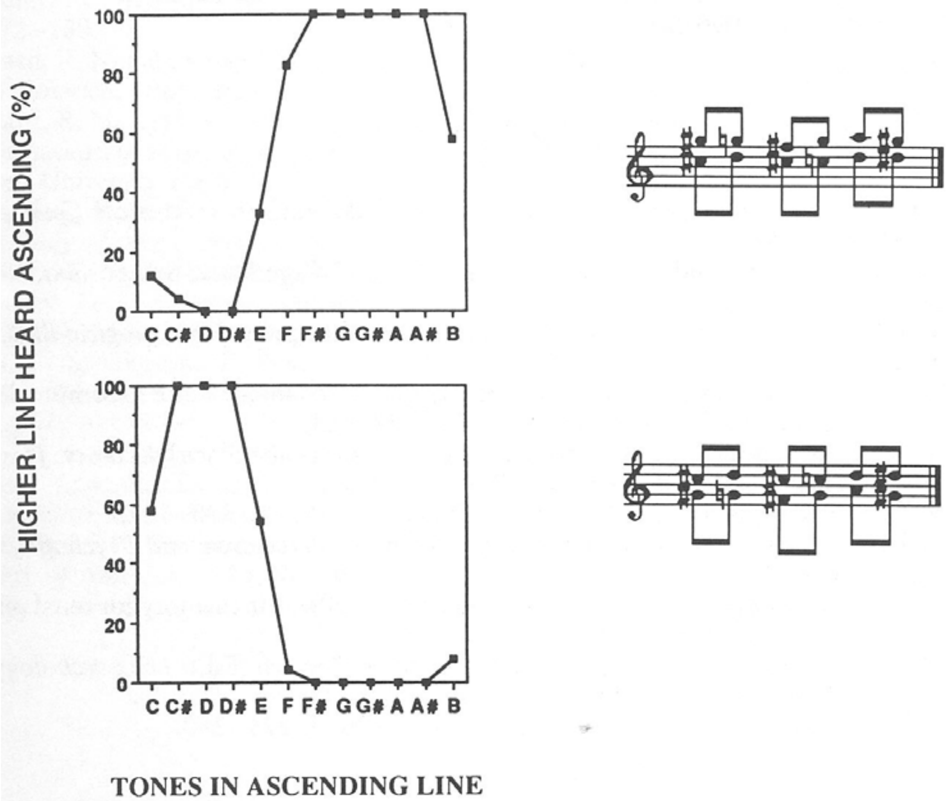

Fig. 10. Representation of the identical series of patterns, as perceive by two different listeners. The diagram on the left shows the judgments of subjects M.F. and K.D., with tones generated under the envelope centered at C_5. In general, such a series of patterns will be heard by an audience in many different ways.

Differences between listeners were also found here in the extent to which judgments were influenced by spectral factors. Such differences have been reported with respect to octave-related complexes by other investigators also (Charbonneau & Risset, 1973; Nakajima et al., 1988; Ohgushi, 1985; Risset, 1971; Ueda & Ohgushi, 1987). Risset (1971) reported that less musical subjects assigned more prominence to spectral characteristics; however Ueda and Ohgushi (1987) obtained a trend in the converse direction. In the present study no pattern of correlation with musical training was found, although the number of subjects was clearly too small to make a realistic evaluation.

The mechanism responsible for this paradoxical phenomenon remains to be investigated. The present findings show, however, that in addition to the processes giving rise to "residue pitch" or "virtual pitch," and also to "spectral pitch" (Goldstein, 1973; Wightman, 1973; Terhardt, Stoll, & Seewann, 1982), a third process is involved in determining the perceived height of a complex tone. This process is one in which pitch class plays a central role. Although it leads to paradoxical effects in artificially contrived situations such as explored here, this process could play a useful role in reducing ambiguity and maintaining consistency in the perception of sounds in our natural environment.[2]

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