Pitch circularity from tones comprising full harmonic series

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This paper describes an algorithm for producing pitch circularity using tones that each comprise a full harmonic series, and reports an experiment that demonstrates such circularity. Banks of 12 tones (i.e., scales) were created, with ***F*0** varying in semitone steps. For each scale, as ***F*0** descended, the amplitudes of the odd-numbered harmonics were reduced relative to the even-numbered ones by 3.5 dB for each semitone step. In consequence, the tone with the lowest ***F*0** was heard as though displaced up an octave. In an experiment employing two such scales, all possible ordered tone pairs from each scale were presented, making 132 ordered tone pairs for each scale. Sixteen subjects judged for each tone pair whether the second tone was higher or lower than the first. The data derived from these pairwise comparisons were subjected to Kruskal's nonmetric multidimensional scaling, and excellent circularities were obtained. Individual differences in the subjects' judgments were also explored. The findings support the argument that musical pitch should be characterized as varying along two dimensions: the monotonic dimension of pitch height and the circular dimension of pitch class. [DOI: 10.1121/1.2931957]

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I. INTRODUCTION

The American National Standards Institute defines pitch as varying along a single monotonic continuum, specifically as "that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from high to low" (ANSI, 1973). However, musicians have long acknowledged that there is a strong perceptual similarity between tones that stand in octave relation. From a musical standpoint, therefore, pitch is regarded as varying along two dimensions: the monotonic dimension of *pitch height* refers to the position of a tone along a continuum from high to low, and the circular dimension of *pitch class* (or *tone chroma*) refers to the position of a tone within the octave (see, for example, Meyer, 1904; Ruckmick, 1929; Bachem, 1948; Shepard, 1964, 1965, 1982; Pickler, 1966; Risset, 1969; Deutsch, 1969, 1973; 1999; Deutsch *et al.* 1987; Burns and Ward, 1982; Patterson, 1986; Ueda and Ohgushi, 1987; Warren *et al.*, 2003). In the Western musical scale, a note is represented first by a letter name, which refers to its position within the octave, and then by a number, which refers to the octave in which it is placed. For example, the symbols E_2, E_3, and E_4 refer to notes of the same pitch class that are placed in different octaves, and the symbols D_3, $G\#_3$, and A_3 refer to notes of different pitch classes that are placed in the same octave. Given these considerations, musical pitch is often described in terms of a helix which completes one full turn per octave (Fig. 1), so that tones that are separated by octaves are depicted as in close spatial proximity (see, for example, Shepard, 1964, 1965, 1982; Burns and Ward, 1982; Ueda and Ohgushi, 1987; Warren *et al.*, 2003).

In a seminal experiment, Shepard (1964) showed that the monotonic and circular dimensions of pitch can be decoupled experimentally. He employed a bank of tones that each consisted of ten partials which were separated by octaves. The amplitudes of the partials were scaled by a fixed, bell-shaped spectral envelope, so that those in the middle of the musical range were highest, while the others fell off gradually in both directions along a log frequency continuum. Such tones were heard as well defined in terms of pitch class, but ambiguously in terms of pitch height. Listeners were presented with ordered pairs of such tones, and they judged for each pair whether it formed an ascending or a descending pattern. When the tones within a pair were separated by a short distance along the pitch class circle, judgments of relative height were determined entirely by proximity. As the distance between the tones along the circle increased, the tendency to follow by proximity decreased, so that when the tones were separated by a half-octave, averaging across pitch classes, ascending and descending judgments occurred equally often.

Using such a bank of tones, Shepard produced an intriguing demonstration. When the pitch class circle was repeatedly traversed in clockwise steps, the impression was created of a scale that ascended endlessly in pitch. When the circle was traversed in counterclockwise steps, the scale appeared to descend endlessly instead. Risset (1969) generated some remarkable variants of this illusion using gliding tones, so giving rise impressions of endlessly ascending and descending glides. Additional work has been carried out demonstrating the importance of proximity in making judgments of relative height for octave-related complexes (see, for example, Ueda and Ohgushi, 1987; Allik *et al.*, 1989; Deutsch, 1991). Further work has shown that pitch circularities can be produced by tones whose components stand in intervals other than the octave (Burns, 1981, Nakajima *et al.*, 1988).

If pitch circularity were confined to tone complexes such as these, its implications could be considered limited on both theoretical and practical grounds. However, if such circularity could also be achieved with a bank of tones that each

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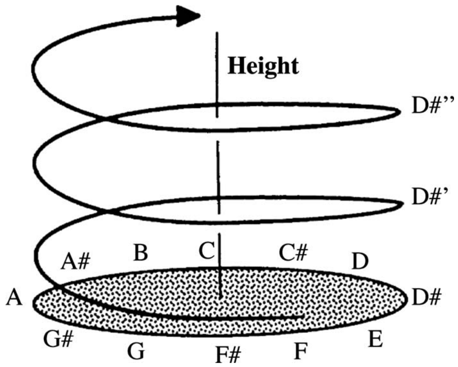

FIG. 1. The pitch helix. Musical pitch is here depicted as varying both along a monotonic dimension of height and also along a circular dimension of pitch class. The helix completes one full turn per octave, so that tones standing in octave relation are in close spatial proximity, as shown by D, D', and D'' in the figure.

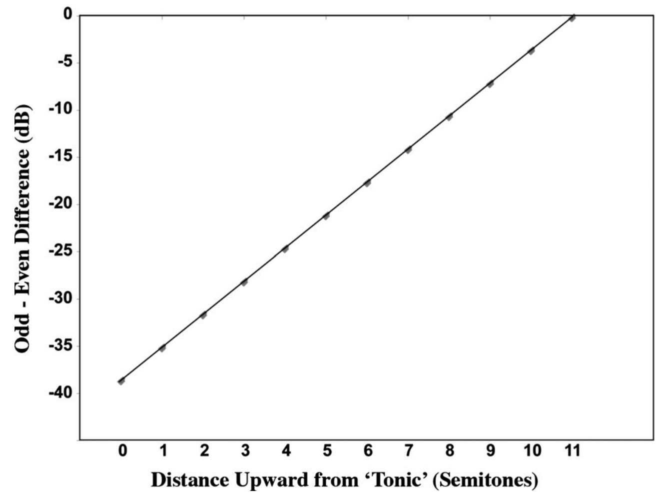

FIG. 2. Relative amplitudes of the odd and even harmonics of the tones employed in the experiment as a function of their positions along the scale. The amplitudes of the odd harmonics relative to the even ones decreased in 3.5 dB steps as their upward distance from the "tonic" decreased in semitone steps (see text for details).

comprised a full harmonic series, then its implications would be broadened, both theoretically and also for musical practice. The present study was carried out in an attempt to achieve such circularity.

Benade (1976) pointed out that a good flute player can smoothly vary the strengths of the odd harmonics of a sustained tone relative to the even ones. Suppose, then, that he begins with the note A_4 ($\boldsymbol{F}0=440$ Hz) with significant amounts of the first six harmonics; this will be heard as well-defined in terms of both pitch class and octave. If the performer then alters his manner of blowing so as to progressively weaken the odd harmonics relative to the even ones, the listener will come to realize, at some point, that he is now hearing a tone at A_5 ($\boldsymbol{F}0=880$ Hz)—exactly an octave higher. However, the transition from the lower to the higher octave will appear quite smooth. This informal observation indicates that the perceived height of a tone consisting of adjacent harmonics might be made to vary in a continuous fashion within the octave, while its pitch class remained constant. Returning to the helical model, one can surmise that to produce differences in pitch height, one need not necessarily travel along a helical path (though the latter analogy still applies to sine waves and to most instrument tones), but can also traverse a straight path along the surface of a cylinder; for example through *D#*, *D#′*, and *D#″* in Fig. 1.

Patterson *et al.* (1993) carried out an experiment to investigate this possibility. They generated a bank of tones, each of which consisted of the first 28 harmonics, with ***F***0s ranging from 31.25 to 1000 Hz. For each tone, the amplitudes of the odd harmonics relative to the even ones were reduced by 9, 18, or 27 dB, and subjects judged the octave in which each tone was placed. Averaging across subjects, at a 27 dB attenuation of the odd harmonics, the tones were judged to be roughly an octave higher, and at 9 and 18 dB attenuations, their perceived heights were judged to be roughly 29% and 77% between the lower and higher octaves. In a further study, Warren *et al.* (2003) presented three subjects with a standard tone and a test tone in which the odd harmonics were attenuated more than those of the standard. The tones were all at $\boldsymbol{F}0=80$ Hz, with harmonics up to 4 kHz, and subjects judged on each trial which of the two presented tones was higher in pitch. Reliable judgments of differences in pitch height were made at around 2 dB attenuation of the odd harmonics.

Given that the pitch of a harmonic complex tone can vary smoothly in height while remaining in the same pitch class, one can theoretically produce circular banks of tones by manipulating the relative amplitudes of the odd and even harmonics. One begins with a bank of 12 tones, each of which consists of the first six components of a harmonic series, and with ***F***0s ranging in semitone steps over an octave. For the tone with the highest ***F***0, the odd and even harmonics are identical in amplitude. Then for the tone with ***F***0 a semitone lower, the amplitudes of the odd harmonics are reduced relative to the even ones, thus raising the perceived height of this tone. Then for the tone with ***F***0 another semitone lower, the amplitudes of the odd harmonics are reduced further, thus raising the perceived height of this tone to a greater extent. One then moves down the octave in this fashion until, for the lowest ***F***0, the odd harmonics no longer contribute to perceived height. The tone with the lowest ***F***0 is therefore heard as displaced up an octave, and so as higher in pitch than the tone with the highest ***F***0. In this way, pitch circularity is achieved.[1]

II. METHOD

A. Stimulus patterns and procedure

Two banks of tones were created, which we shall refer to as *scales*. Each scale consisted of 12 tones, and each tone comprised the first six components of a harmonic series. For convenience, we shall refer to the tone with the lowest ***F***0 as the *tonic* of the scale. For the first scale, the tonic was A_4 (440 Hz), and for the second scale it was $F\#_4$ (370 Hz). For both scales, as ***F***0 moved down in semitone steps, the amplitudes of the odd harmonics relative to the even ones decreased by 3.5 dB (see Fig. 2). Specifically, for the tone with the highest ***F***0 (tone 11 in the figure) the odd and even harmonics were equal in amplitude. For the tone with ***F*0** a semitone lower (tone 10 in the figure), the odd harmonics were 3.5 dB lower than the even ones. For the tone with ***F*0** a semitone lower (tone 9 in the figure), the odd harmonics were 7.0 dB lower than the even ones. Thus for the tone with lowest ***F*0** (tone 0 in the figure) the odd harmonics were 38.5 dB lower than the even ones.

To achieve the above pattern of relationship for harmonic pairs 1 and 2, and harmonic pairs 3 and 4, the even harmonics were consistently high in amplitude, while the odd harmonics decreased in amplitude as the scale descended. To achieve the same pattern of relationship for harmonic pairs 5 and 6, harmonic 5 was consistently low in amplitude while harmonic 6 increased in amplitude as the scale descended (see Fig. 3). To reduce the overall amplitude differences between the tone complexes, these were adjusted slightly, leading to the pattern of amplitude relationships for the different harmonics shown in Table I. The tones were 500 ms in duration with 5 ms rise and fall times and were generated with harmonics in sine phase at a sample rate of 44.1 kHz.

For each scale, 132 ordered tone pairs were created, such that each pitch class was followed once by every other pitch class. On each trial a tone pair was presented, and the subjects judged whether it formed an ascending or a descending pattern. For each scale, the tone pairs were presented in 11 blocks of 12. Each pitch class served as the first tone of a pair once in each block, and no pitch class occurred in two successive tone pairs within a block. Other than this, the tone pairs were presented in haphazard order. The tones within a pair followed each other without pause. There were 4 s intervals between pairs within a block, and 1 min intervals between blocks. The subjects were tested in two sessions, one with the scale generated under the A_4 tonic and the other generated under the $F\#_4$ tonic. The order of presentation of the two scales was strictly counterbalanced across subjects. In addition, two subjects served in six extra sessions, and so made judgments on each scale four times altogether.

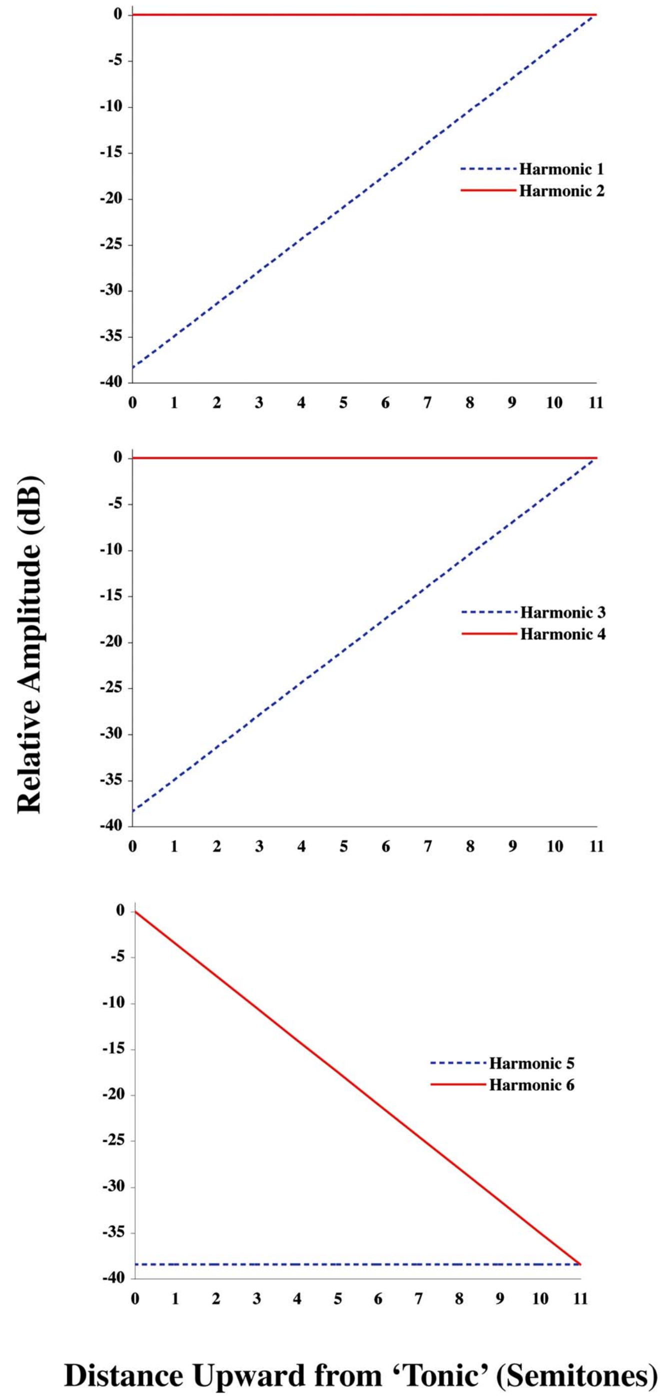

FIG. 3. (Color online) Progression of the relative amplitudes of harmonics 1 and 2, harmonics 3 and 4, and harmonics 5 and 6 as ***F*0** moves upward from the "tonic."

B. Instrumentation

The tones were generated on a G5 computer, using the software package PD,[2] and were recorded onto a compact disk. The compact disks were played on a Denon DCD-815 compact disk player, the output of which was passed through a Mackie CR 1604-VLZ mixer, then through a Powerplay HA 4000 headphone distribution amplifier, and presented to subjects diotically in soundproof booths via Sennheiser HD 25 SP headphones at a level of roughly 70 dB sound pressure level (SPL).

C. Subjects

Sixteen students at UCSD served as subjects in the experiment. These were 5 male and 11 female, with an average age of 24.4 years (range 20–30 years), and an average of 8.3 years of musical training (range 0–20 years). They comprised 13 right handers and 3 non-right-handers, as determined by the handedness questionnaire of Varney and Benton (1975).[3] The subjects were selected on the basis of having normal hearing as determined by audiometry, and making no more than 2 errors on a pretest in which they judged whether 120 pairs of sine wave tones formed ascending or descending patterns. In the pretest, the tones were 500 ms in duration, and there were no gaps between tones within a pair. The tones within pairs were separated by 2, 4, 6, 8, or 10 semitones, in either the upward or the downward direction.

TABLE I. Relative amplitudes (in dB) of the harmonics of the 12 tones comprising each circular scale. The distance upward along the scale is given in semitones.[a] For one scale, harmonic 1 of the tonic was 440 Hz (corresponding to A_4), and for the other scale, harmonic 1 of the tonic was 370 Hz (corresponding to $F\#_4$).

Distance upward along scale (semitones)	Harmonic number 1	2	3	4	5	6
0 ("tonic")	−40.5	−2	−40.5	−2	−40.5	−2
1	−36	−1	−36	−1	−39.5	−4.5
2	−31.5	0	−31.5	0	−38.5	−7
3	−28	0	−28	0	−38.5	−10.5
4	−24.5	0	−24.5	0	−38.5	−14
5	−21	0	−21	0	−38.5	−17.5
6	−17.5	0	−17.5	0	−38.5	−21
7	−14	0	−14	0	−38.5	−24.5
8	−10.5	0	−10.5	0	−38.5	−28
9	−8	−1	−8	−1	−39.5	−32.5
10	−5.5	−2	−5.5	−2	−40.5	−37
11	−3	−3	−3	−3	−41.5	−41.5

[a]It was later discovered that due to a typographical error, harmonic 5 of tone 9 was set at −39.9 dB rather than −39.5 dB. However, further testing revealed no perceptual effect resulting from this 0.4 dB amplitude discrepancy

III. RESULTS

A. Overall findings

Figure 4 shows the percentages of judgments based on pitch class proximity, as a function of semitone separation between the tones within a pair. The data are shown for the A_4 and $F\#_4$ scales separately, in each case averaged over all tone pairs and over all subjects. As can be seen, when the tones within a pair were separated by a small distance along the pitch class circle, judgments tended overwhelmingly to be based on proximity. This tendency was reduced with increasing distance between the tones along the pitch class circle, yet remained high even at the largest value of semitone separation between the tones.

A 5×2 within-subject analysis of variance (ANOVA) was performed, with value of semitone separation along the pitch class circle (1–5) and scale ($F\#_4$, A_4) as factors. (The value of 6 semitones was omitted from the analysis since at this value the same distance between the tones along the pitch class circle is traversed in either direction, so that proximity cannot be used as a cue.) The overall effect of semitone separation was highly significant [$F(4,60)=69.05$, $p<0.001$]. The overall effect of scale was nonsignificant ($F<1$), and the interaction between value of semitone separation and scale was nonsignificant [$F(4,60)=2.335$, $p>0.05$]. Pairwise comparisons revealed highly significant differences between all values of semitone separation: 1 vs 2 semitones, $p<0.02$; 2 vs 3 semitones, $p<0.001$; 3 vs 4 semitones, $p<0.001$; 4 vs 5 semitones, $p<0.001$.

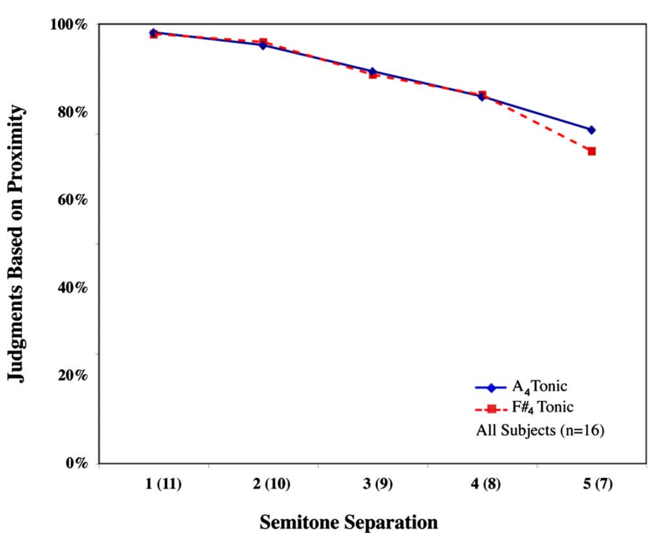

FIG. 4. (Color online) Percentages of judgments based on pitch class proximity as a function of semitone separation along the pitch class circle between the tones within a pair. The data are shown for the A_4 and $F\#_4$ scales separately, averaged across all subjects.

To determine the extent to which pitch circularity was achieved, the data were subjected to Kruskal's nonmetric multidimensional scaling, using ALSCAL (see Borg and Groenen, 2005). Figure 5 shows, for the $F\#_4$ and A_4 scales separately, the MDS solutions derived from the results pooled from all subjects, and it can be seen that excellent circularities were obtained from both scales. Figure 6 shows the stimulus configurations derived from each of the two subjects who were tested four times on both the $F\#_4$ and A_4 scales, and it can be seen that excellent circularities were obtained here also.

We can then ask whether violations of proximity, though uncommon, were related to the positions of the tones along the scale. To this end we plotted, for the $F\#_4$ and A_4 scales separately, the percentages of judgments that a tone was heard as the higher or lower of a pair, when this judgment was in violation of proximity. Figure 7 shows the results pooled from all subjects. As can be seen, an orderly, though small, tendency emerged under both scales to judge tones as higher with increasing upward position along the scale.

A 12×2 within-subject ANOVA was performed, with position along the scale (0–11) and scale ($F\#_4$, A_4) as factors. The overall effect of position along the scale was highly significant [$F(11,165)=5.715$, $p<0.001$]. The overall effect

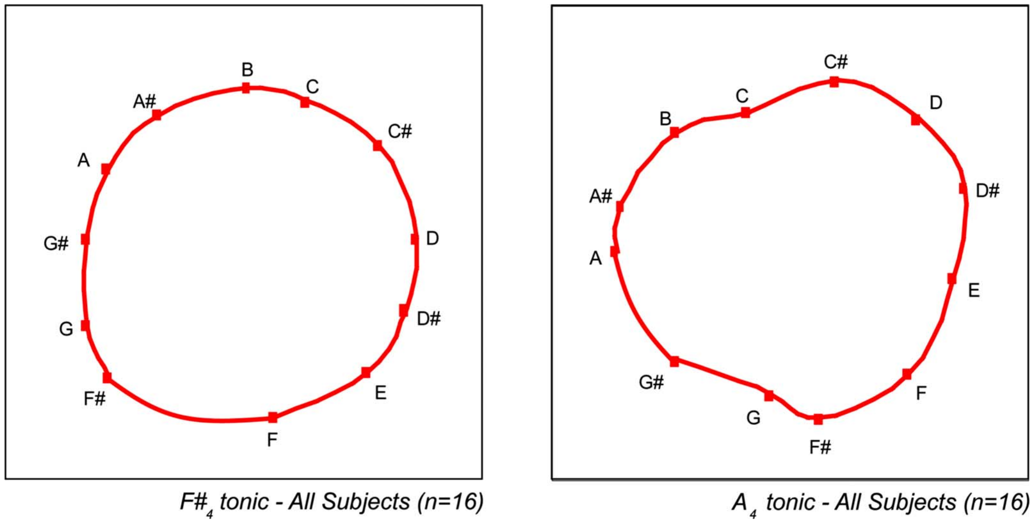

FIG. 5. (Color online) Multidimensional scaling solutions derived from the pooled data from all subjects, for tones produced under the scales based on the $F\#_4$ and A_4 tonics separately. For the $F\#_4$ tonic, stress $-1=0.0111$; $R^2=0.9991$. For the A_4 tonic, stress $-1=0.0113$; $R^2=0.9990$.

of scale was nonsignificant $(F=1)$. The interaction between scale and position along the scale was marginally significant $[F(11,165)=1.898,\ p=0.043]$, indicating a marginal influence of overall spectral region on the behavior of the circularity effect.

B. Individual differences

Although all subjects overwhelmingly judged the relative heights of the tones on the basis of proximity at small values of semitone separation, individual differences in judgment appeared at larger values. Since the tones were so configured that their spectral density necessarily increased with increasing position along the scale, it was hypothesized that some subjects might have been influenced by this cue. To examine this possibility, we divided the subjects into two groups on the basis of their judgments at the tritone, where proximity could not have been involved in their judgments. We found that, taking the data from both scales, six of the subjects based at least 21 of the 24 possible judgments at the tritone on this principle: they judged tones as higher when they were in higher positions along the scale, and as lower when they were in lower positions. These we designated as sp ("spectral") subjects. For the remaining ten subjects, judgments were scattered in haphazard fashion as a function of position along the scale; these we designated as pc ("pitch class") subjects. The six sp subjects comprised five right handers and one non-right-hander, two male and four female, with an average age of 24.5 years (range 23–26 years) and an average of 7.8 years of musical training (range 2–14 years). The 10 pc subjects comprised eight right handers and two non-right-handers, three male and seven female, with an average age of 24.4 years (range 20–30 years) and 8.6 years of musical training (range 0–20 years).

Figure 8 displays the tendency to base judgments on proximity as a function of semitone separation along the pitch class circle between the tones within a pair, for the pc and sp subjects separately, and for the $F\#_4$ and A_4 scales separately. As can be seen, for both scales, the pc subjects showed a remarkably strong tendency to follow by proximity, even at the largest value of semitone separation between the tones within a pair. However, the sp subjects tended less to follow by proximity as the values of semitone separation between the tones increased.

Given these apparent differences between the two subgroups, statistical analyses were carried out taking the pc and sp subjects separately. Where value of semitone separation was concerned, 5×2 within-subject ANOVAs were performed, with value of semitone separation (1–5) and scale ($F\#_4$, A_4) as factors. Taking the pc subjects alone, the overall effect of semitone separation was highly significant $[F(4,36)=30.99,\ p<0.001]$, the overall effect of scale was nonsignificant $(F<1)$, and the interaction between value of semitone separation and scale was also nonsignificant $[F(4,36)=2.09,\ p>0.05]$. Taking the sp subjects alone, the overall effect of value of semitone separation was significant $[F(4,20)=210.34,\ p<0.001]$, the overall effect of scale was nonsignificant $(F<1)$, and the interaction between the value of semitone separation and scale was also nonsignificant $[F(4,20)=2.37,\ p>0.05]$.

Figure 9 displays the percentages of judgments that a tone was the higher or lower of a pair when these judgments were in violation of proximity, as a function of the position of the tone along the scale, for the pc and sp subjects separately, and for the A_4 and $F\#_4$ scales separately. As can be seen, for both scales, the sp subjects showed an increasing tendency to judge the tone as higher with increasing position along the scale; however, this was not true of the pc subjects.

To evaluate the statistical significance of these factors, 12×2 within-subject ANOVAs were performed, with position along the scale (0–11) and scale $(F\#_4, A_4)$ as factors. For the pc subjects alone, the overall effect of position along the scale was nonsignificant $(F<1)$, the overall effect of scale was nonsignificant $(F<1)$, and the interaction between position along the scale and scale was marginally significant $[F(11,99)=2.01;\ p<0.05]$, indicating for these subjects a marginal influence of overall spectral region on the behavior of the circularity effect. Taking the sp subjects alone, the overall effect of scale was nonsignificant $(F=1)$, the overall

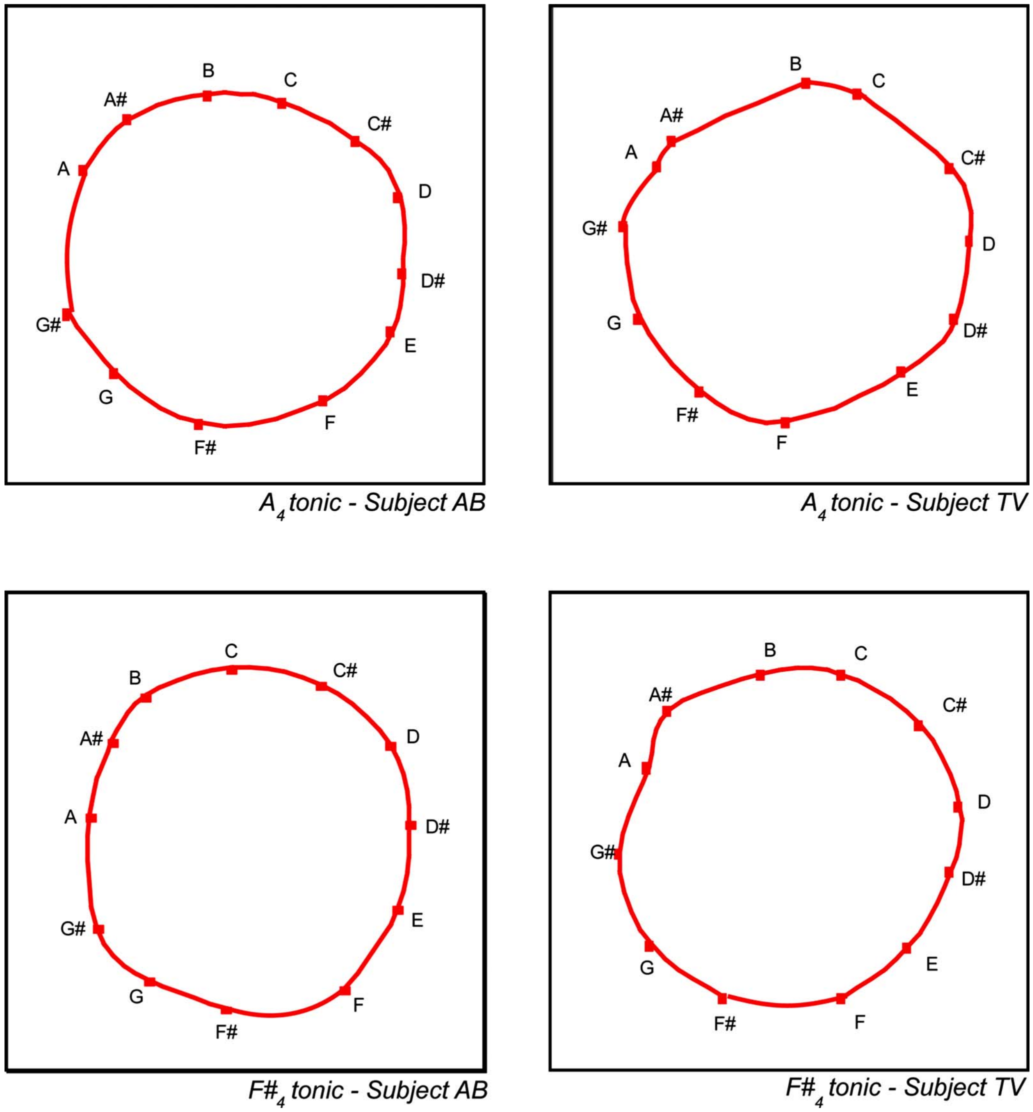

FIG. 6. (Color online) Multidimensional scaling solutions derived from the data from two subjects individually, for tones produced under the scales based on the $F\#_4$ and A_4 tonics separately. Subject AB: for the A_4 tonic, stress $-1=0.0099$; $R^2=0.9992$; for the $F\#_4$ tonic, stress $-1=0.0108$; $R^2=0.9991$. Subject TV: for the A_4 tonic, stress $-1=0.0211$; $R^2=0.9967$; for the $F\#_4$ tonic, stress $-1=0.0083$; $R^2=0.9995$.

effect of position along the scale was highly significant $[F(11,55)=29.14,\ p<0.001]$, and the interaction between scale and position along the scale was nonsignificant $[F(11,55)=1.63,\ p>0.05]$.

Despite these differences between the pc and sp subjects, the judgments of both subgroups were more consistent with a two-dimensional solution than a one-dimensional one. For judgments of the pc subjects on the A_4 scale, the one-dimensional solution yielded stress$-1=0.3506$ ($R^2=0.5885$), whereas the two-dimensional solution yielded stress$-1=0.0076$, ($R^2=0.9996$); on the $F\#_4$ scale, the one-dimensional solution yielded stress$-1=0.3691$ ($R^2=0.5487$), whereas the two-dimensional solution yielded stress$-1=0.0123$ ($R^2=0.9988$). For judgments of the sp subjects on the A_4 scale, the one-dimensional solution yielded stress$-1=0.1515$ ($R^2=0.9240$), whereas the two-dimensional solution yielded stress$-1=0.0191$ ($R^2=0.9979$); on the $F\#_4$ scale, the one-dimensional solution

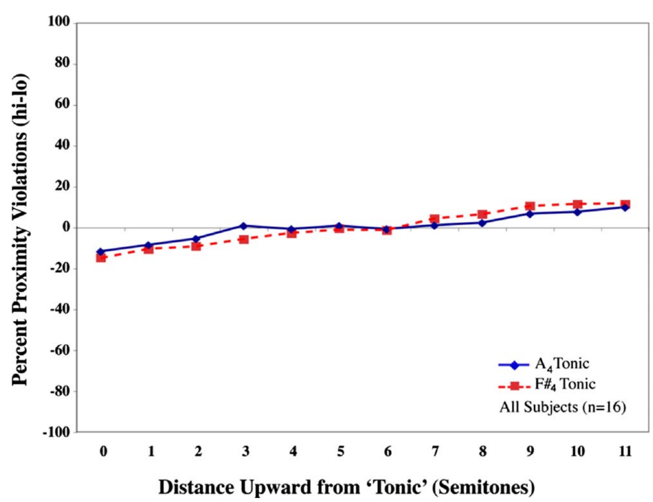

FIG. 7. (Color online) Percentages of judgments that a tone was the higher or lower of a pair, when these judgments were in violation of proximity, plotted as a function of the position of the tone along the scale. The data are shown for the A_4 and $F\#_4$ scales separately, averaged across all subjects.

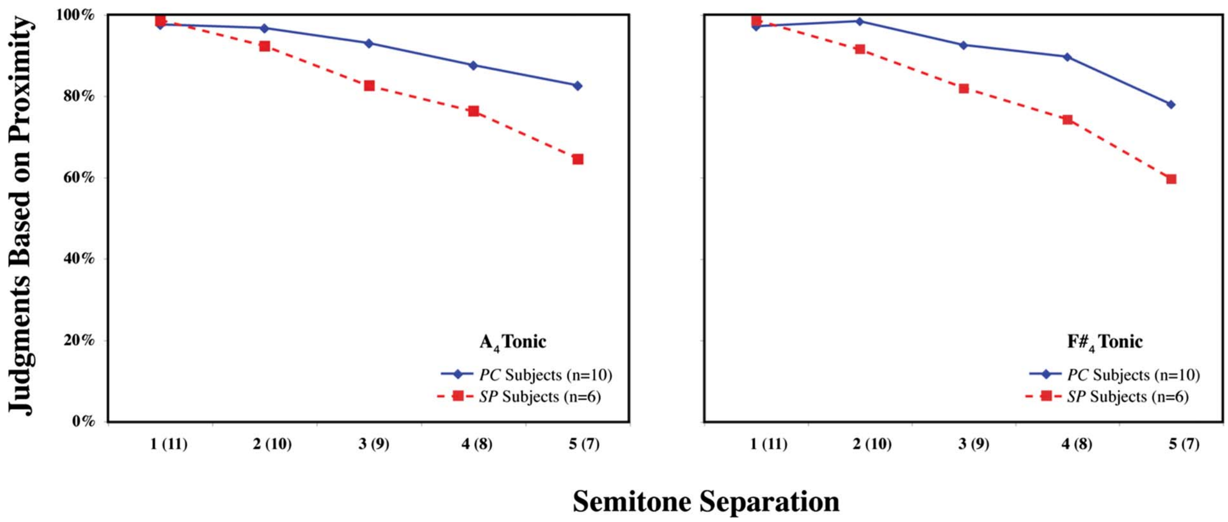

FIG. 8. (Color online) Percentages of judgments based on pitch class proximity as a function of semitone separation along the pitch class circle between the tones within a pair. The data are shown for the A_4 and $F\#_4$ scales separately and for the pc and sp subjects separately.

yielded stress−1=0.1660 (R^2=0.9081), whereas the two-dimensional solution yielded stress−1=0.0107 (R^2=0.9993).

IV. DISCUSSION

The findings obtained in the present study demonstrate that pitch circularity is not confined to octave-related (or equal-interval) complexes, but can also occur with sequences of tones that each comprise a full harmonic series. The circular component of pitch can therefore be decoupled experimentally from the height component, even for tones that are similar in spectral composition to those produced in the natural environment.

Normann *et al.* (2001), using a different algorithm, created banks of harmonic complex tones which were rendered ambiguous with respect to height by the addition of subharmonic partials. When subjects were asked to judge the relative heights of such tones, their judgments reflected considerable ambiguity. From statistical analyses of these judgments, the authors concluded that at least 39% of the subjects showed perceptions that were significantly indicative of a circular component of pitch.

We now enquire into the neural substrates of the monotonic and circular components of pitch. Warren *et al.* (2003) used functional magnetic resonance imaging (fMRI) to study patterns of brain activation in response to tone sequences of two types. In the first type, the harmonic components of the tones were at equal amplitude while $F0$ varied, so that here pitch class and pitch height varied together. In the second type, pitch class was held constant but the relative amplitudes of the odd and even harmonics were varied, so that differences in pitch height alone were produced. The first type of sequence gave rise to activation specifically in a region anterior to primary auditory cortex, whereas the second type produced activation specifically in a region posterior to primary auditory cortex. Given these findings, we can hypothesize that the circularity obtained in the present study might have been due to activation in the anterior region identified by Warren *et al.* However, the signals in the present

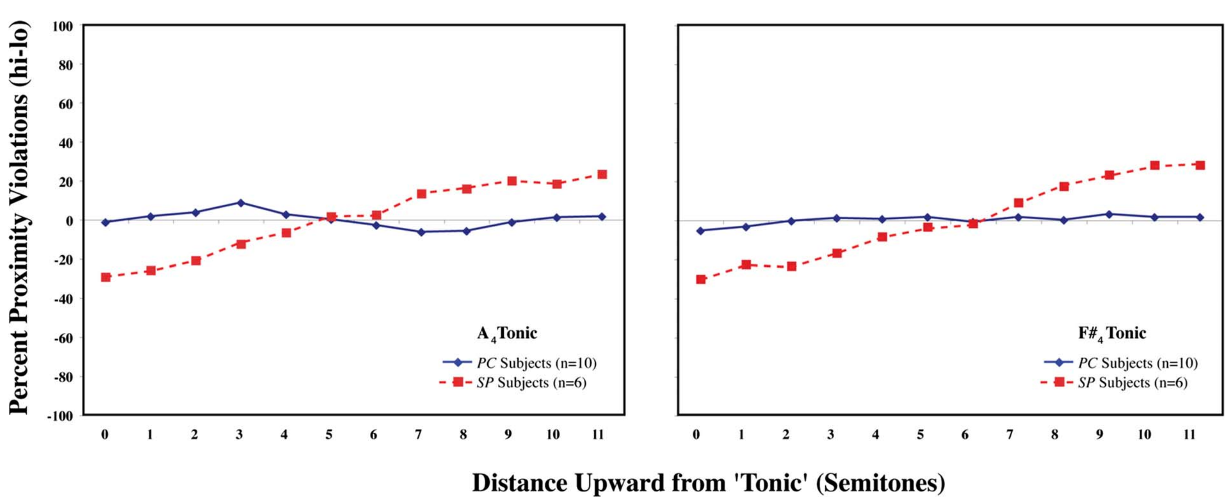

FIG. 9. (Color online) Percentages of judgments that a tone was the higher or lower of a pair, when these judgments were in violation of proximity, plotted as a function of the position of the tone along the scale. The data are shown for the A_4 and $F\#_4$ scales separately and for the pc and sp subjects separately.

study were produced by co-varying both ***F*0** and the relative amplitudes of the odd and even harmonics, so that both the regions identified by Warren *et al.* might have been involved in the effects described here. At a different level, evidence has recently been provided in the gerbil that the ventral nucleus of the lateral lemniscus is organized as a neuronal pitch helix, with pitches organized helically from top to bottom, with one octave for each turn of the helix (Langner, 2005). This finding places the lateral lemniscus as a possible source of pitch circularity.

We now turn to the basis of the individual differences in the strength of the circularity effects obtained here, i.e., between the pc and the sp subjects. Smoorenberg (1970) created successive pairs of tones, with each tone consisting of two adjacent harmonics of a missing fundamental. Either ***F*0** fell while the spectral region of the harmonics rose, or ***F*0** rose while the spectral region of the harmonics fell. Subjects judged for each pair of tones whether it rose or fell in pitch. Considerable individual differences were found in the tendency for judgments to be based on missing ***F*0** as opposed to spectral region. Houtsma and Flourens (1991) elaborated on this paradigm, and confirmed the presence of pronounced individual differences in making such judgments. Laguitton *et al.* (1998) employed a similar paradigm, but with two, three, or four adjacent harmonics. They found that left handers tended more than right handers to base their judgments on spectral region rather than ***F*0**. Schneider *et al.* (2005) presented right-handed musicians with a similar task and found that those subjects who tended to base their judgments on spectral region showed a pronounced rightward, rather than leftward, asymmetry of the grey matter volume within the pitch-sensitive lateral Heschl's gyrus. Given this body of evidence, we may hypothesize that the individual differences found in the present paradigm could reflect similar differences in brain organization, with those subjects who were more sensitive to position of the tone along the scale (i.e., sp subjects) corresponding to those who based their judgments on spectrum in the earlier experiments. No effect of handedness was found in our study; however, the number of subjects tested was too small to assess handedness differences convincingly.

It should be noted that the results obtained here, as those obtained previously with octave-related complexes (Shepard, 1964; Risset, 1969; Ueda and Ohgushi, 1987; Allik *et al.*, 1989; Deutsch, 1991) and other equal-interval complexes (Burns, 1981; Nakajima *et al.*, 1988), reflected a strong influence of the principle of proximity in making judgments of relative pitch: tone pairs were heard as ascending or descending depending on which was the most proximal direction along the pitch class circle. Pitch proximity has been shown to be a powerful organizing principle in other contexts also, such as in the scale illusion (Deutsch, 1975), stream segregation for rapid sequences of single tones (Bregman, 1990; Bregman and Campbell, 1971; Dowling, 1973; Van Noorden, 1975), and short term memory for pitch (Deutsch, 1978).

At a more cognitive level, it has been shown that when a listener attributes a key to a musical passage, he or she invokes a complex set of similarity relationships between the 12 pitch classes, so that 3–5 dimensions of pitch have been proposed at this higher level of abstraction (see, in particular, Shepard, 1982; Krumhansl, 1990; and Lerdahl, 2001 for detailed discussions).

Finally, using the algorithm described here, we have generated demonstrations of endlessly ascending and descending scales and glides.[4] These circular demonstrations are analogous to those produced by Shepard and by Risset using octave-related complexes (see, for example, Houtsma *et al.*, 1987). The present findings also lead to the conjecture that by using the present algorithm for determining the relative amplitudes of the odd and even harmonics, one might be able to create banks of tones that are perceptually similar to those produced by natural instruments but that nevertheless exhibit pitch circularity. Such tones could then be made to vary in infinitely small steps along the dimensions both of pitch height and of pitch class; this could prove useful in the development of algorithms for new music.

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[1]In an earlier experiment, Deutsch and coworkers implemented this basic idea but employed a different set of parameters than those used in the present study (Deutsch, Dooley, Dubnov, Henthorn, and Wurden, paper presented at the 150th Meeting of the Acoustical Society of America, Minneapolis, October 2005). However, in this earlier experiment, the tones were low pass filtered and the effects of the resultant phase shifting were unknown.

[2]This software package was created by Miller Puckette, and is available for download at http://crca.ucsd.edu/~msp/software.html (date last viewed 4/22/08).

[3]Those subjects who scored 8–10 "rights" on the handedness questionnaire were designated as right handers; the remainder were designated as non-right-handers.

[4]Demonstrations of pitch circularity produced by sequences of tones generated in accordance with the present algorithm are available on request.

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