The Psychophysics of Harmony Perception: Harmony is a Three-Tone Phenomenon

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ABSTRACT: In line with musical "common sense" (but contrary to the century-old tradition of musical psychophysics), we show that harmony is an inherently three-tone phenomenon. Previous attempts at explaining the affective response to major/minor chords and resolved/unresolved chords on the basis of the summation of interval dissonance have been notably unsuccessful, but consideration of the relative size of the intervals contained in triads leads directly to solutions to these historical problems. At the heart of our model is Leonard Meyer's idea from 1956 concerning "intervallic equidistance" – i.e., the perception of "tension" inherent to any three-tone combination that has two intervals of equivalent size (e.g., the augmented chord). By including the effects of the upper partials, a psychophysical explanation of the perceived sonority of the triads (major>minor>diminished>augmented) and the affective valence of major and minor chords is easily achieved. We conclude that the perceptual regularities of traditional diatonic harmony are neither due to the summation of interval effects nor simply arbitrary, learned cultural artifacts, but rather that harmony has a psychophysical basis dependent on three-tone combinations.

Submitted 2006 February 24; accepted 2006 March 22.

KEYWORDS: *harmony, psychophysics, dissonance, tension, major mode, minor mode*

THE psychophysical study of music has an honorable history going back at least to Helmholtz (1877). Particularly since the 1960s and the widespread use of electronic techniques to create and measure musical tones with great precision, the perception of two-tone intervals and the influence of upper partials on the perception of intervals have been rigorously examined, and several important insights gained. Some of the successes of this reductionist scientific approach to the perception of music will be reviewed below, but a discussion of the science of music must begin with a statement of the complete failure thus far to account for the core phenomena of diatonic harmony on psychophysical principles. Most significantly, the fact that some chords sound stable, final and resolved, while others sound unstable, tense and unresolved cannot be explained solely on the basis of the summation of interval dissonance among tones and their upper partials. Moreover, although the positive and negative affective valence of major and minor chords is salient both to young children and to adults from diverse cultures, this also has not been explained. As a consequence of the simultaneous ability to explain the basics of interval perception (and therefore the emergence of diatonic and pentatonic musical scales worldwide) and yet the inability to explain the perception of even the simplest of three-tone harmonies, there is a widespread (if often implicit) acknowledgement that harmony perception may be a result of the learning of the arbitrary tone patterns commonly used within the so-called Western idiom, with little acoustic rationale for these patterns other than the consonance of certain intervals.

THREE-TONE PSYCHOPHYSICS

Our approach to harmony perception has been to build on the established findings of interval research (and the important role of upper partials) by asking further questions about the psychophysics of three-tone combinations. It is of course likely that, at some point, the effects of learning, cultural traditions and indeed individual differences will play a dominant role in determining the perception of complex musical compositions, but the perceptual "stability" ("sonority", "tonality", "consonance", "pleasantness", "beauty") of the triads of diatonic harmony has been measured in diverse human populations, and rather consistent results obtained. For example, Roberts (1986) showed that, for both musicians and non-musicians, major chords are perceived as more consonant than minor chords, which are in turn perceived as more consonant than diminished chords, followed by augmented chords (Figure 1a & 1b). Similar experiments including triads that contain a whole-tone or semitone dissonant interval (Cook, 1999) showed the same sequence of sonority, with triads containing a dissonant interval being perceived as less sonorous than the augmented chords (Figure 1c).

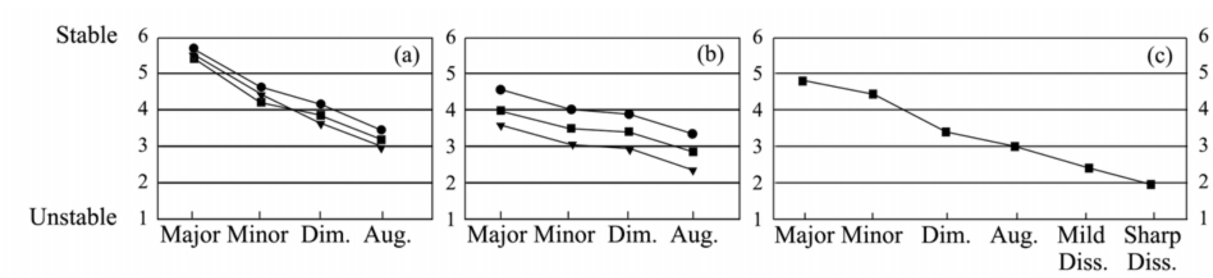

Fig. 1. Evaluation of the relative "stability" (~ "consonance") of the triads. The data in (a) are from American musicians (Roberts, 1986), those in (b) are from American non-musicians (Roberts, 1986), and those in (c) are from Japanese non-musicians (Cook, 1999). The symbols in (a) and (b) refer to various inversions of the triads, but in all cases the sequence of stability is: major>minor>diminished>augmented. In (c), the mildly dissonant chords contained one whole-tone interval and one 7- or 8-semitone interval. The sharply dissonant chords contained one semitone interval and one 6- or 7-semitone interval.

Pitch height, pitch timbre and especially the interval configuration of the dissonant chords have effects on such judgments, but the basic pattern of triad perception (for children and adults, peoples of the West and Far East, musicians and non-musicians) is not a matter of empirical dispute. Given the extensive research results since the 1960s on the perception of musical intervals, it is reasonable to ask if the perception of triadic harmonies can be explained as the summation of interval effects? The answer is an unambiguous "no", but many textbook discussions of the psychoacoustics of music (i) note the successes of the psychophysics of interval perception, (ii) point out the relative consonance of the intervals of the diatonic scales, and then (iii) suggest that the basics of harmony perception have thus been accounted for. Unfortunately, every careful examination of this issue has produced negative results, indicating that even the relatively simple issue of three-tone combinations cannot be reduced to intervals.

The most detailed explication of the psychophysics of harmony can be found in Parncutt's (1989) monograph. There he advocated a model of pitch perception that included the effects of the masking and fusion of tones, and of course the important role of upper partials. Details of the model differ somewhat from preceding work by Terhardt (1978), but the approach is solidly within the empirical framework first pursued by Helmholtz (1877) and is the essential starting point for a scientific discussion of music perception. There are many laudable aspects of Parncutt's work, but, in the present context, the negative results concerning triad perception are the most noteworthy. That is, on the basis of a rigorous model of interval perception, he was able to calculate the total "tonalness" (~"musical consonance", p. 142) of three-tone combinations, and found that the augmented chord had a ***higher*** tonalness than two of the major chords and all three of the minor chords (Table 1). He was forced to conclude that:

> "The [perceptual] dissonance of the augmented triad… is not reflected by its [theoretically] calculated tonalness; it appears to have cultural rather than sensory origins." (p. 141)

That statement is highly debatable, to say the least. To accept such a view, we would need to conclude that the common perception of the unresolved tension of the augmented chord is a consequence of cognitive factors, and that, acoustically, the chord itself is inherently more sonorous than most of the resolved major and minor chords, but that the sonority is imperceptible because of learning. This flies in the face of all experience of diatonic music and is contrary to the results of perceptual experiments (e.g., Roberts, 1986). It should be noted that the difficulty of explaining the perception of triads on the basis of interval consonance is not unique to Parncutt's work. On the contrary, other interval-based explanations of harmony run into similar quantitative problems. Table 1 shows a comparison of the relative sonority of common diatonic triads as calculated from the dissonance models of Helmholtz (1877/1954), Plomp & Levelt (1965), Kameoka & Kuriyagawa (1969), Parncutt (1989), and Sethares (1999). In fact, all of these model predictions are influenced by the number and amplitude of the upper partials that are assumed, so it is possible that parameter-tweaking could produce slightly better results. Nevertheless, Table 1 shows that the theoretical curves used by these authors to explain the relative consonance of the intervals of diatonic scales produce results concerning the total sonority of triads that are simply inconsistent with experimental results (e.g., Figure 1). The empirical rank order (major>minor>diminished>augmented) is ***not*** reproduced by any of the interval models.

Table 1. The relative sonority of common triads in root and inverted positions.

Chord Class	Interval Structure	Expt. Sonority Roberts	Theoretical Sonority Helmholtz	P&L	K&K	Parncutt	Sethares	C&F
	4-3	1	3	4	1	1	4	1
I. Major	3-5	2	**9**	**11**	**11**	6	**8**	5
	5-4	3	1	2	6	3	2	4
	3-4	4	3	4	1	4	4	2
II. Minor	4-5	5	1	2	6	6	2	3
	5-3	6	**9**	**11**	**11**	**10**	**8**	6
	3-3	7	**13**	**13**	6	9	**12**	12
III. Diminished	3-6	8	11	8	9	**5**	10	7
	6-3	9	11	8	9	8	10	10
IV. Augmented	4-4	10	**5**	10	13	**2**	12	13
	5-2		**5**	**6**	**1**		**6**	8
V. Suspended 4th	2-5		**5**	**6**	**1**		**6**	11
	5-5		8	**1**	**1**		**1**	9

Experimental values are from Roberts (1986) and theoretical values are from Helmholtz (1877, p. 193), Plomp & Levelt (1965), Kameoka & Kuriyagawa (1969), Parncutt (1989, p. 140), Sethares (1999, p. 92) and Cook & Fujisawa (this paper). Striking anomalies in the sonority ranking of these models are underlined in bold type.

Precise determination of the sequence of perceived sonority of triads uninfluenced by mean pitch height and timbre will require further experimental work, but all indications thus far are that the resolved (major and minor) chords are universally perceived as more sonorous than the unresolved (diminished, augmented and suspended 4th) chords. Models of harmony perception must, at the very least, reproduce that overall pattern, but clearly do not (Table 1). Despite the failure of the interval-based models in explaining harmony even at this rather crude level, it bears emphasis that the dissonance curves have been remarkably successful in explaining interval perception. As shown in Figure 2, interval models that include the effects of the upper partials have found peaks of consonance at most of the notes of the diatonic scale (e.g., Partch, 1947/1974; Plomp & Levelt, 1965; Kameoka & Kuriyagawa, 1969; Sethares, 1993, 1999). That result alone indicates the importance of interval effects (and the contribution of upper partials to interval perception) for explaining the emergence of music based on diatonic scales. If, however, the sonority of triads cannot be explained as the summation of interval effects, we must ask how other factors can be brought into a more comprehensive model. Clearly, one of the first topics to examine is the interval-spacing of three-tone combinations.

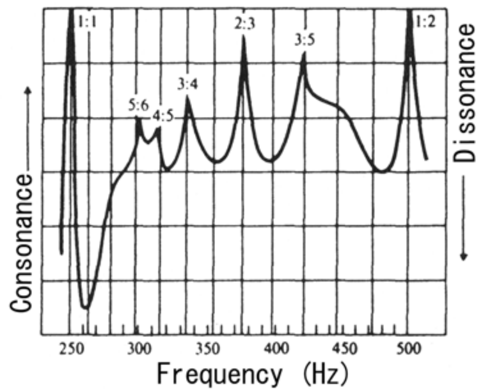

Fig. 2. The curve obtained by including the first six upper partials of tones in calculating the total dissonance of intervals (Plomp & Levelt, 1965). Noteworthy are the peaks of consonance obtained at many of the intervals of the major and minor diatonic scales. Different tuning systems produce peaks precisely on or slightly off of the peaks of consonance, but most listeners are tolerant of slight deviations from maximal consonance.

INTERVALLIC EQUIDISTANCE

Although most previous studies on the musical triads have been made within the framework of traditional music theory, Leonard Meyer (1956, pp. 157-196) has developed ideas about harmony from the perspective of Gestalt psychology. Simply stated, Meyer's argument concerning the sonority of triads is that the perception of two neighboring intervals of equivalent size – heard either melodically or harmonically – produces a sense of tonal "tension" that can be resolved only by pitch changes resulting in unequal intervals. [The importance of unequal steps in most traditional musical scales has been discussed by others, notably, Lerdahl (2001), but the only discussion we have found of harmony explicitly in relation to the magnitude of neighboring intervals is that of Meyer (1956).] Just as a dissonant interval of 1-2 semitones is perceptually the most salient two-tone combination (and "demands" resolution toward unison or toward any of several consonant intervals), the most salient three-tone harmonies are those where the three tones are equally spaced (and, in the Western tradition, "demand" resolution toward a major or minor chord). Meyer suggested that the perception of such tension in the diminished and augmented chords (and chromatic scales) is a basic Gestalt, possibly concerned with the grouping of tones according to their relative distance from one another in pitch space. When any three tones are equally spaced (on a logarithmic scale) such that there is no natural grouping of the middle tone with either the higher or lower tone, it is "caught in the middle", producing an effect of "tension", "ambiguity" and "instability" – not unlike the Necker cube in the visual domain. We have elaborated on Meyer's idea in the form of a psychophysical model of three-tone combinations and, as discussed below, maintain that the model suffices to account for the perceptual differences in the sonority of the harmonic triads without relying on ideas from traditional harmony theory. Moreover, it leads directly to a plausible (evolutionary) explanation of the characteristic affect of the major and minor chords.

Intervallic equidistance is a structural feature common to the diminished and augmented chords in root position and one that distinguishes them from the major and minor chords. Moreover, the semitone spacing of the upper partials of such chords indicates why the inversions of the diminished chord (with unequal intervals) also exhibit tension (Figure 3). As discussed below, the tension produced by equal intervals neatly accounts for the resolved/unresolved character of all 10 triads of traditional diatonic music. Although not a part of traditional harmony theory, a coherent set of "tension chords" can be defined in terms of the semitone spacing of tones and used to reconstruct harmony theory on a psychophysical basis. It is understandable that during the Renaissance the tension chords with no discernible connection to the centerpiece of all traditional ideas on harmony, the major chord, would be dismissed as "dissonances", but their re-evaluation in light of the sensibilities of modern harmony perception is long overdue. Here we show that, by shifting the focus of harmony theory from the major chord to the inherently unresolved tension chords, the regularities of traditional harmony theory can be seen in a new light.

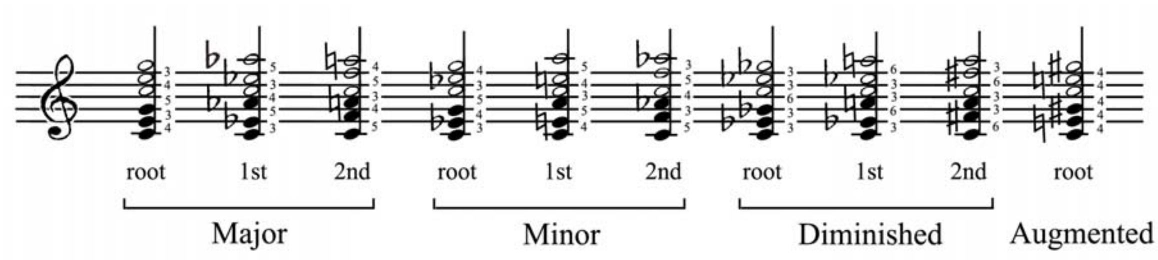

Fig. 3. The interval structure of the triads of Western harmony. The triads are shown as quarter notes and the first set of upper partials for each chord is shown as half notes. Interval sizes in semitones are shown as small integers. *None* of the major and minor chords, but *all* of the diminished and augmented chords show repeating intervals of the same size – and consequently the "tension" characteristic of intervallic equidistance. (Consideration of further upper partials complicates the story, but there is a paucity of intervallic equidistance in the major and minor chords, and an abundance in the diminished and augmented chords.)

It should be noted that Meyer asserted the psychological validity of intervallic equidistance solely on the basis of his understanding of musical phenomena. Justification as a general law of Gestalt psychology or as an auditory manifestation of Gestalt grouping principles clearly requires further empirical study. Nevertheless, however the instability of the "tension chords" might be explained psychologically, judgment concerning the harmoniousness of these and the other triads of diatonic music is empirically unambiguous (Figure 1).

It is therefore possible to classify all three-tone chords into three distinct perceptual categories: (1) sonorous chords containing unequal, consonant intervals, (2) tense chords containing "intervallic equidistance", and (3) dissonant chords containing one or more dissonant intervals. Traditional music theory categorizes the dissonant and tense chords together, but Meyer's idea suggests that the factors leading to their unresolved character are distinct. On the one hand, there are tonal combinations that are unresolved solely because of the presence of a lower-level interval dissonance, while other combinations are unresolved specifically because of the intervallic equidistance. Distinguishing between these two cases leads to a classification of the triads as shown in Figure 4. Our approach has therefore been to attempt to establish the empirical reality of this distinction (Cook, 1999, 2002a, 2002b; Cook et al., 2001, 2002a, b, 2003, 2004, 2006) and to model dissonance and tension as distinct factors (Fujisawa, 2004; Fujisawa et al., 2004) before entering into the full complexity of traditional harmony theory.

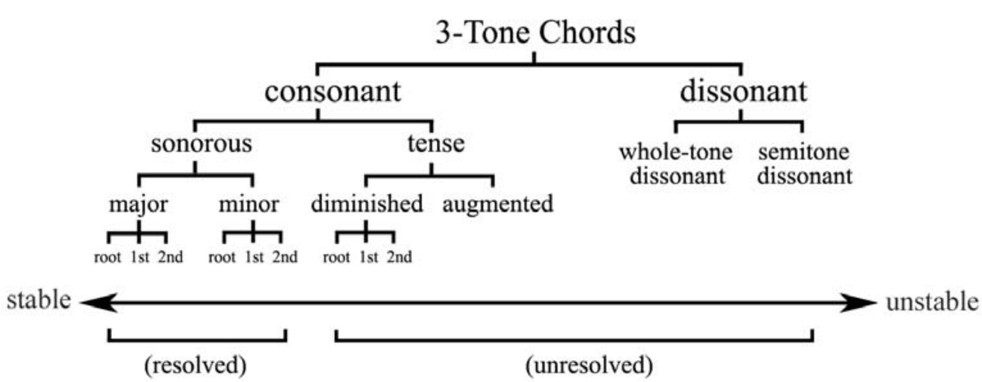

Fig. 4. A classification of all three-tone combinations, in which the relative "stability" is influenced by both two-tone effects (consonance/dissonance) and three-tone effects (sonority/tension).

A PSYCHOPHYSICAL MODEL

As illustrated in Figures 3 and 4, Meyer's idea that neighboring intervals of the same magnitude are the source of harmonic tension has some face validity, but formalization is yet needed for the idea to become a psychophysical model. Since the source of tension is thought to be the presence of equivalent intervals, the difference of interval size for any three-tone combination can be taken as the basic structural unit for a model of tension. In our model, the function used to express the psychological tension (calculated from the difference in interval sizes) is taken to be Gaussian in shape – with a maximal value when the difference is zero, and a minimum of zero when the absolute difference between the intervals is 1.0 or greater. This is illustrated in Figure 5.

From what is already known about interval perception, the character of three-tone combinations is likely to be influenced by the number and amplitude of the upper partials of each tone in the triad, so that we include the effects of upper partials in the calculation of triadic tension. Specifically, a tension (t) value is obtained from each triplet combination of upper partials.

$$t = v \cdot \exp\left[-\left(\frac{y-x}{\alpha}\right)^2\right] \qquad \text{Eq. 1}$$

where $\boldsymbol{v}$ is the product of the relative amplitudes of the three partials, $\boldsymbol{\alpha}$ (~0.60) is a parameter that determines the steepness of the fall from maximal tension; $\boldsymbol{x}$ and $\boldsymbol{y}$ are, respectively, the lower and upper of the two intervals in each tone triplet, defined as $\boldsymbol{x} = \log(f_2/f_1)$ and $\boldsymbol{y} = \log(f_3/f_2)$, where the frequencies of the three partials are $f_1 < f_2 < f_3$ (in Hertz). The total tension (T) is then calculated by repeated application of Eq. 1 to every triplet of the partials among the three tones:

$$T = \sum_{i=0}^{n-1}\sum_{j=0}^{n-1}\sum_{k=0}^{n-1} t(x_{ij}, y_{jk}, v_{ijk}) \qquad \text{Eq. 2}$$

The results of model calculations are presented in Figures 6, 7 and 8 for three-tone chords with one fixed interval of 3, 4 or 5 semitones, and a second interval that is allowed to vary from 0.0 to 9.0 semitones. In Figure 6a, the growing complexity of the tension curves caused by the addition of more and more upper partials is illustrated. Figure 6b shows the curves obtained when all upper partials (F0~F5) are included in the calculation based on four different assumptions about the relative amplitude of the partials.

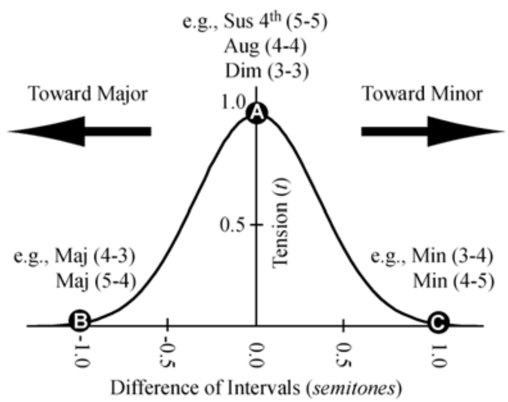

Fig. 5. A psychophysical model of three-tone tension. Tension is perceived when two equivalent intervals are heard (point A), but not when the two intervals differ by one (or more) semitones (points B and C). Those are the locations on the "tension curve" for which there is unambiguous empirical data (in the form of traditional harmony). A Gaussian function is used because it reflects the tolerance of most listeners for slight mistuning of chords by effectively broadening the regions of perceived tension and resolution, but the exact shape of the curve remains empirically uncertain. Here and elsewhere we assume twelve-tone equitempered tuning (for further details, see Fujisawa, 2004).

The most important result of such calculations is that (regardless of which tension curve is examined) peaks of ***maximal*** tension are obtained at the unresolved (diminished, augmented and suspended fourth) chords and all of their inversions. Similarly, troughs of minimal tension are obtained at the resolved (major and minor) chords and all of their inversions. It bears emphasis that these results are a direct consequence of Meyer's idea of intervallic equidistance (plus the contribution of upper partials) and accurately reflect what is known about the perception of the triads of traditional harmony theory.

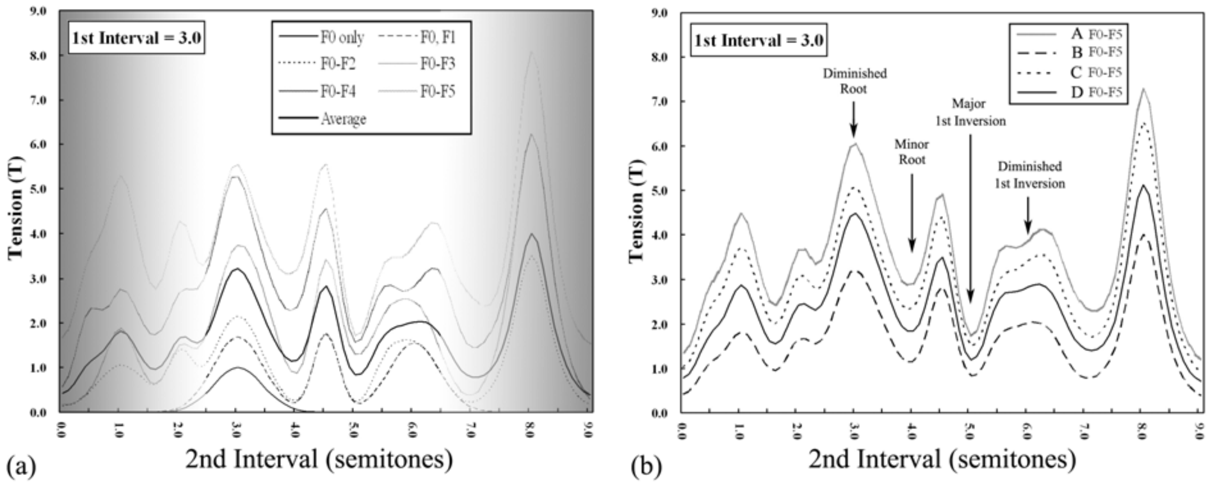

Fig. 6. The tension curves obtained using the model shown in Figure 5, and assuming a lower interval of 3 semitones for various triads. In (a), the effects of adding upper partials on the theoretical tension curves are shown. The grey regions to the left and right are where interval dissonance is strong. Although tension values are calculated for those regions as well, the salience of the three-tone tension is arguably overpowered by the dissonance of small intervals. In (b), the mean curves for four different assumptions about the relative amplitudes of 6 partials are shown (A, all partials with amplitude 1.0; B, product of partial amplitudes used, with amplitudes decreasing as 1/n; C, all partials set to the amplitude of the lowest frequency partial in each triplet; and D, all partials set to the minimum amplitude of each triplet). Note that troughs of minimal tension are found at the major and minor chords, and peaks of maximal tension are found at the diminished chords, regardless of the details of upper partial structure.

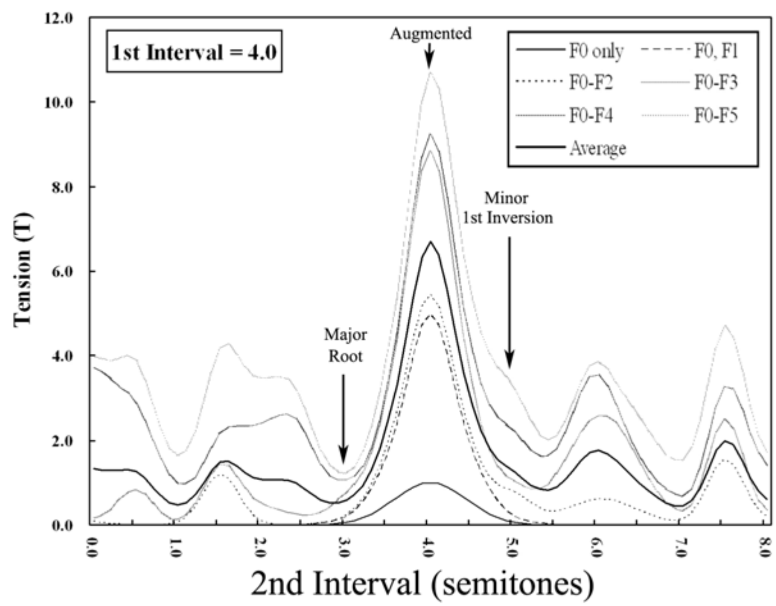

Fig. 7. The tension curves obtained using the model in Figure 5, and assuming a lower interval of 4 semitones. Arrows indicate the two main troughs where resolved chords lie, and a peak of tension at the augmented chord

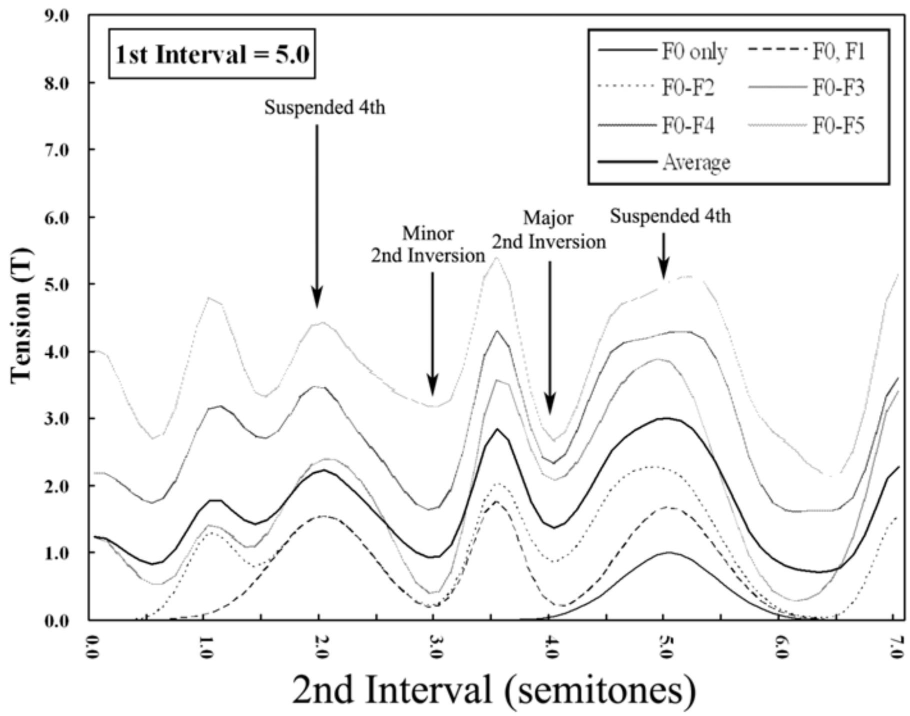

Fig. 8. The tension curves obtained using the model in Figure 5, and assuming a lower interval of 5 semitones. Arrows again indicate the locations of major and minor chords with low tension and "suspended 4th" chords with high tension.

The fact that troughs and peaks in the tension curves are obtained at, respectively, the resolved and unresolved chords of traditional harmony theory shows that the model is in fundamental agreement with findings on the human perception of three-tone harmonies. Moreover, the fact that similar curves are obtained regardless of the number of partials (>1) or their relative amplitudes is indication of the robustness of the model. Of further interest for non-diatonic music are the occasional peaks and troughs in the curves that lie at locations other than semitone intervals. This is a topic of our current experimental research, and will not be discussed here.

A theoretical value for the overall perceptual "instability" of chords can be obtained if both the total dissonance among tone pairs and the total tension among tone triplets are added together. We have used a dissonance model (Eq. 3) similar to that of Sethares (1999) to calculate dissonance (d):

$$d = v \cdot \beta_3 \left\lfloor \exp(-\beta_1 x^{\gamma}) - \exp(-\beta_2 x^{\gamma}) \right\rfloor \qquad \text{Eq. 3}$$

where $\boldsymbol{v}$ is the product of the relative amplitudes of the two tones and $\boldsymbol{x}$ is the interval, defined as $\boldsymbol{x} = \log(f_2/f_1)$ and the parameters are $\boldsymbol{\beta_1}$ (~-0.80)), $\boldsymbol{\beta_2}$ (~-1.60), $\boldsymbol{\beta_3}$ (~4.00), $\boldsymbol{\gamma}$ (~1.25). The total dissonance (D) is obtained by summing the dissonance of all pairs of partials:

$$D = \sum_{i=0}^{n-1} \sum_{j=0}^{n-1} d(x_{ij}, v_{ij}) \qquad \text{Eq. 4}$$

Finally, the total instability (I) of any three-tone chord can then be calculated as the weighted sum of the total dissonance and the total tension:

$$I = D + \delta T \qquad \text{Eq. 5}$$

where δ (~0.207) is a parameter that de-emphasizes the tension of triads, and gives relative instability scores that are in rough agreement with the experimental data shown in Figure 1 (see Table 1 and Table A2 in the Appendix for details).

Inevitably, the use of such model equations involves parameters that are set to give results in accord with experimental data. The parameters for Equation 3 give a maximal dissonance at about 1.0 semitone, significant dissonance at 2.0 and little dissonance for larger intervals. As previously shown by Plomp & Levelt (1965), Kameoka & Kuriyagawa (1969) and others, such a model reproduces experimental data reasonably well, provided that the presence of upper partials is assumed. Such modeling is not unproblematical, but the total dissonance curve thus obtained (e.g., Figure 2) produces peaks and valleys that are consistent with traditional diatonic music and with experimental data on interval perception. This theoretical curve is, by all previous accounts, a major success in explaining diatonic music.

In order to obtain a good fit with experimental data on harmony perception (Table 1), we have chosen an upper partial structure similar to that used by Sethares (1993), i.e., six partials with relative amplitudes of 1.0, 0.88, 0.76, 0.64, 0.58 and 0.52. Nearly identical results are obtained with other assumptions about the upper partial structure of the tones (see Figure 6). Although further improvements in the fit between experimental and theoretical values may be possible, the basic result of distinguishing between the resolved and unresolved chords is obtained if at least one upper partial is included, regardless of the upper partial details. The final sequence of sonority for all triads using our model is that shown in Table 1 (with further details shown in Table A2 in the Appendix).

MAJOR AND MINOR MODES

The curves shown in Figures 6-8 indicate that the resolved/unresolved character of triads has a straightforward psychophysical basis that is quite distinct from previous arguments based solely on the summation of interval dissonance. If indeed the pitch qualities of "tension" and "relaxation" can be described in terms of the relative size of the two intervals contained within a triad, it is then of interest to ask if the positive/negative emotions of the major and minor chords might have a related psychophysical basis dependent solely on relative interval size.

The classical theory of harmonic mode focuses entirely on the intervals of major and minor thirds ("we could consider thirds … as the sole elements of all chords… Thus, we should attribute to them all the power of harmony", Rameau, 1722, p. 39) and then gets into well-known complications in explaining the role of the minor third in the first inversion of the major chord and the role of the major third in the first inversion of the minor chord. The minor third contributes to the minor sonority of the minor triad in root position when a third tone is placed a fifth above the tonic, but the same interval of a minor third magically participates in a major chord if the third tone is placed at a major third below the tonic or at a minor (!) sixth above the tonic. This is of course elaborately explained away within the Ptolemaic epicycles of traditional harmony theory, but the lack of an unambiguous status of the isolated minor third interval (and similarly for the major third) strongly suggests that two-tone combinations may be too simple a basis to explain harmonic phenomena.

The affective valence of major and minor harmonies is one of the oldest puzzles in all of Western music. Today, it is fashionable to dismiss the common perception of major and minor modes as being merely a cultural artifact, but it is undeniable that, whatever the extent of learning and cultural reinforcement that we all experience, there is a deep bias both for children as young as 3 years-old (Kastner & Crowder, 1990) and for adults from the East and the West to hear "sadness" in the minor chords and "happiness" in the major chords. Most musicians and music psychologists are of course reluctant to describe the affect of the major and minor modes with simple dichotomies such as "happy" and "sad", but it is an empirical fact that, holding all other factors constant, most people hear "negative affect" in the minor chords and "positive affect" in the major chords. The emotional response to major and minor music has been evaluated in many studies (see, Scherer, 1995, and Gabrielsson & Juslin, 2003, for reviews) and often discussed in the framework of classical Western music (Cooke, 1959). Moreover, experimental studies of isolated major and minor triads give similar results (Figure 9).

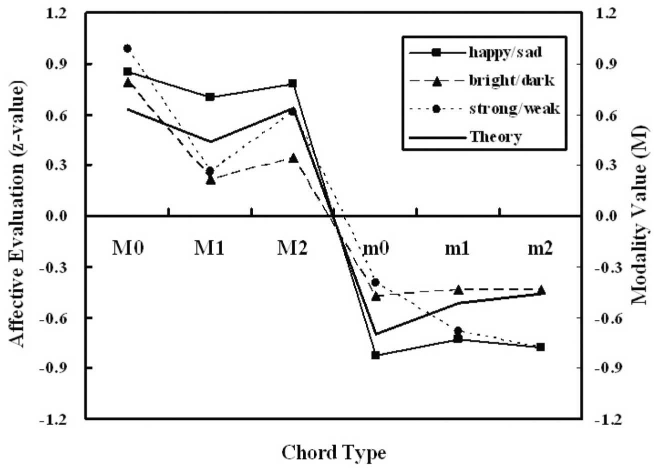

Fig. 9. The results of three experiments in which 20 (18 or 66) undergraduate non-musicians evaluated the bright/dark [3] (happy/sad or strong/weak) quality of 72 (24 or 12) isolated major (M0, M1, M2) and minor (m0, m1, m2) chords presented in random (pseudo-random or fixed) order in various keys and at various pitch heights. Indications of differences among the inversions of these chords are of interest, but, in any case, the affective distinction between major and minor is clear. The thick solid line shows our model predictions (see Appendix).

How might the positive and negative valence of the major and minor modes also be expressed in terms of relative interval sizes? Figure 10 shows a model that is again based on the difference in magnitude of the two intervals in each three-tone triad. That is, modality (m) is defined as:

$$m = -v \cdot \left[\frac{2(y-x)}{\varepsilon}\right] \exp\left\{-\left[\frac{-(y-x)^4}{4}\right]\right\} \qquad \text{Eq. 6}$$

where $\boldsymbol{v}$ again determines the relative contribution of the three partials, $\boldsymbol{x}$ and $\boldsymbol{y}$ are the lower and upper intervals, respectively, and the parameter, $\boldsymbol{\varepsilon}$, 1.558 is set to give a positive modality score of 1.0 for the major chord in root position and a negative modality score of –1.0 for the minor chord in root position. Similar to calculation of the total tension of tone combinations, calculation of the total modality (M) requires application of Equation 6 to all triplet combinations of the upper partials of the three tones:

$$M = \sum_{i=0}^{n-1}\sum_{j=0}^{n-1}\sum_{k=0}^{n-1} m(x_{ij}, y_{jk}, v_{ijk}) \qquad \text{Eq. 7}$$

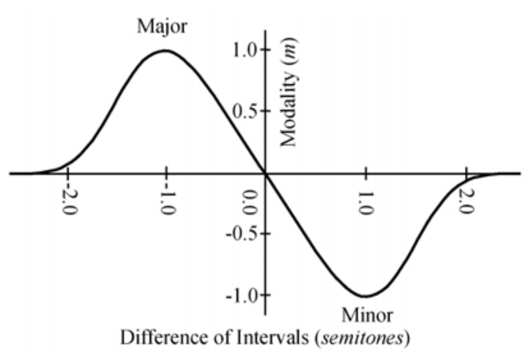

Fig. 10. The modality curve. The difference in the magnitude of the intervals (upper minus lower) of a triad will determine its positive (major) or negative (minor) modality (Fujisawa, 2004; Cook et al., 2006).

As was the case for the total tension curves for various interval combinations (Figures 6-8), the total modality curves are influenced by the presence of upper partials. It is again noteworthy, however, that the peaks and troughs arise at ***all*** of the inversions of the major and minor chords, respectively, regardless of the number of upper partials (>1) or their relative amplitudes. In other words, similar to the tension calculation, the modality calculation is robust with regard to the role of the upper partials. These aspects are illustrated in Figures 11, 12 and 13 for triads with a lower interval of 3, 4 and 5 semitones, respectively, and an upper interval that is allowed to vary.

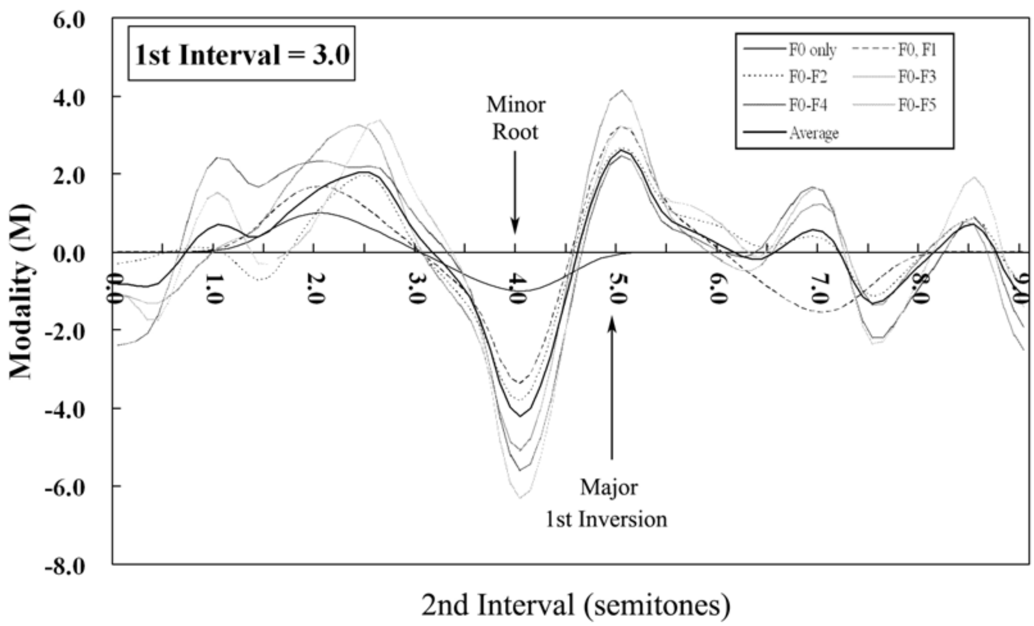

Figure 11: The modality curves for triads containing a lower interval of three semitones and an upper interval ranging between 0.0 and 9.0 semitones. Note the strongly negative modality value at the (3-4) minor triad and the strongly positive value at the (3-5) major triad.

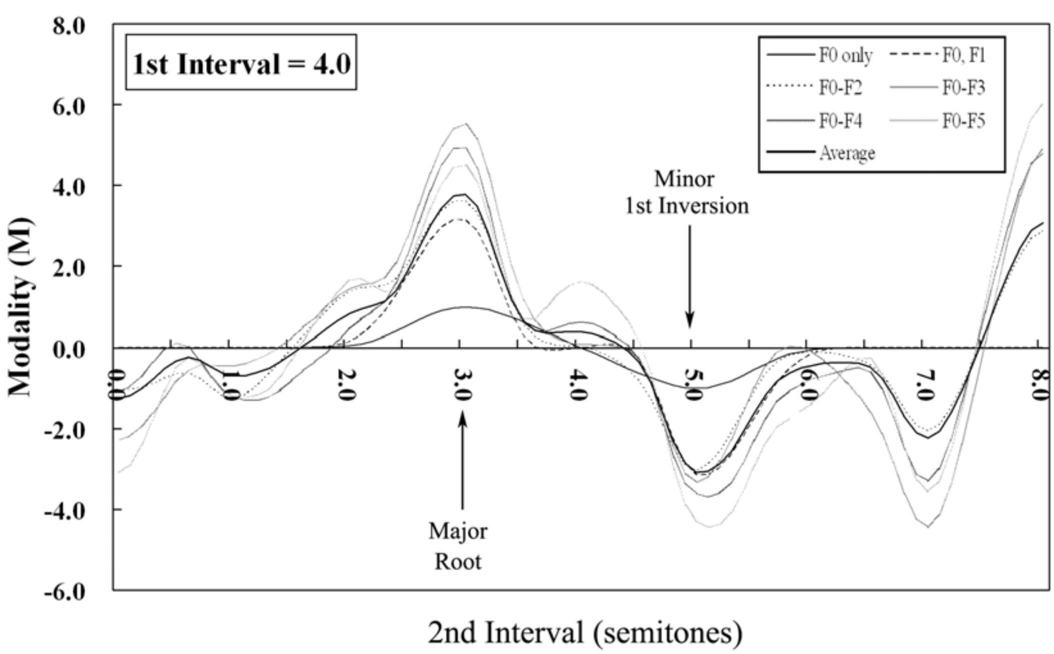

Fig. 12. The modality curves for triads containing a lower interval of 4 semitones and an upper interval ranging between 0.0 and 8.0 semitones. Note the strongly positive modality value at the (4-3) major triad and the strongly negative modality value at the (4-5) minor triad.

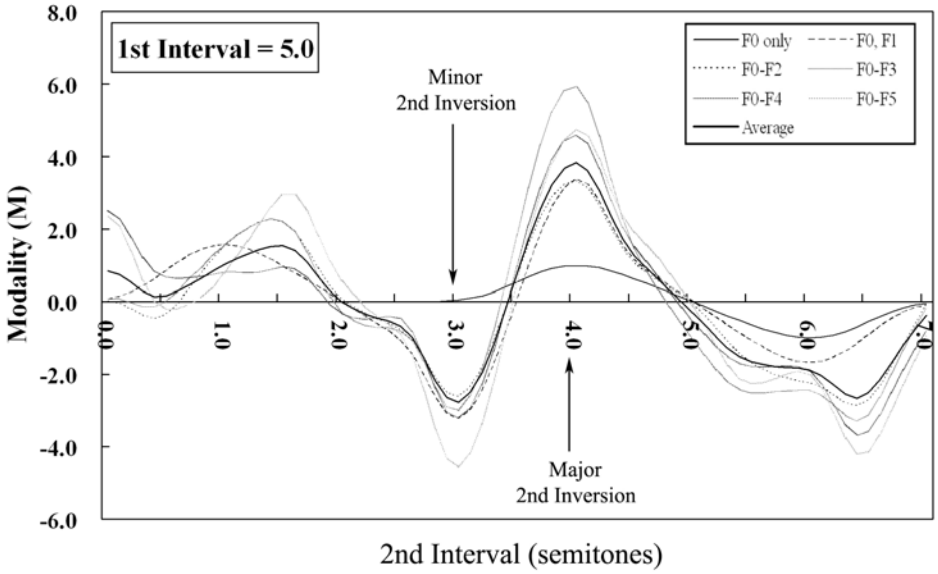

Fig. 13. The modality curves for triads containing a lower interval of 5 semitones and an upper interval ranging between 0.0 and 7.0 semitones. Note the strongly negative modality value at the (5-3) minor triad and the strongly positive modality value at the (5-4) major triad.

The theoretical curves in Figures 11-13 indicate that the major and minor chords have a structural simplicity that is hidden behind the complex rules of traditional harmony theory, but is revealed by viewing triads in relation to intervallic equidistance. In essence, major chords have an overall upper partial structure where tone triplets show a larger lower interval and a smaller upper interval (e.g., 4-3), and vice versa for minor chords. On a piano keyboard, this structure is self-evident for the root and 2nd inversion of the major triad (and root and 1st inversion of the minor triad), but it also holds true for the 1st inversion of the major triad and the 2nd inversion of the minor triad if the upper partial structure is examined. In effect, Meyer's concept of intervallic equidistance (plus the effects of upper partials) allows for a quantitative account of both the resolved/unresolved and the major/minor character of three-tone chords.

The psychophysical model outlined above is, in essence, a restatement of common sense concerning musical harmony, so it is of interest to see how the complexities of traditional harmony theory might be re-expressed on this basis. First of all, it is evident that, if the unsettled ambiguity of the tension chords is taken to be the most salient feature of three-tone harmonies, then major and minor chords represent the only two possible resolutions of chordal tension. Schoenberg (1911) predicted that the major and minor modes would disappear and go the way of the other church modes with acceptance of chromatic music ("As for laws established by custom, however – they will eventually be disestablished. What happened to the tonality of the church modes, if not that? … We have similar phenomena in our major and minor." pp. 28-29). If intervallic equidistance is the source of harmonic tension, however, valleys of resolution are the inevitable reverse side of tension. In so far as the 12-tone scale is the raw material from which harmonies are constructed, there are two and only two pitch directions to move from the unstable tension of equivalent intervals, i.e., to the major and minor chords (Figure 5). So, not only is it unlikely that music will evolve in a direction of unabated chromatic tension without the use of chords with resolved, asymmetrical intervals, it is also clear why, from the abundance of various church modes, only two have remained prevalent until the present day. While various modal scales remain possible and indeed in common use, only the major and minor directions are available for movement from harmonic tension to resolved chords.

The clearest example of these core relationships among tension, major and minor chords can be seen in relation to the augmented chord. Given the starting point of intervallic equidistance, the rising or falling direction of semitone movement of any tone determines the mode of resolution: major (downward) or minor (upward) (Figure 14). It is a remarkable regularity of harmonic phenomena in general that pitch changes in any of the tension chords (diminished, augmented or suspended 4th) give similar results (see the Appendix).

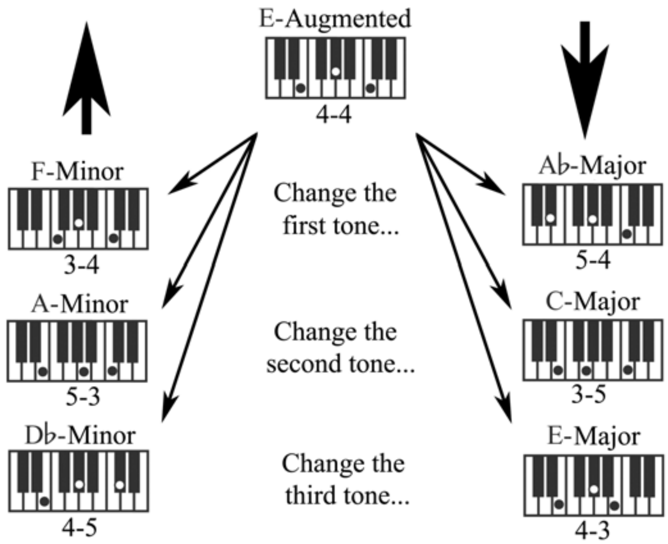

Fig. 14. A semitone increase in any tone of an augmented chord results in a minor chord, while a semitone decrease results in a major chord (interval structure is noted below each chord).

In other words, the major, minor and tension chords are related to one another by semitone steps. This fundamental pattern among all of the consonant triads can be illustrated as a Cycle of Modes (Figure 15a). The traditional view that the essential difference between the major and minor chords is the semitone shift in the interval of a third (Figure 15b) is of course correct, as far as it goes, but implicitly dismisses all other chords as "dissonances" – which, technically, is not correct. By bringing the (unresolved, but not dissonant!) diminished and augmented chords into a broader theory of harmony that is based on three-tone psychophysics, the classification of all triads shown in Figure 4 is implied.

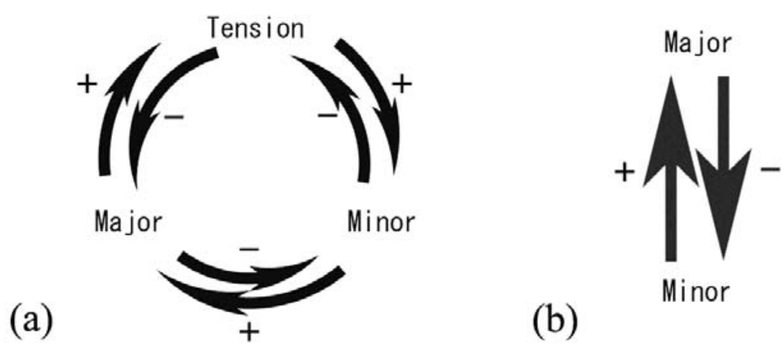

Fig. 15. (a) The Cycle of Modes. The plus and minus symbols indicate increases or decreases in semitone steps. If all chords containing interval dissonances are avoided, semitone increases lead from tension to minor to major and back to tension harmonies indefinitely, whereas semitone decreases show the reverse cycle. (b) The traditional view of the major and minor chords is only part of the cycle.

Using Meyer's idea of relative interval size, many of the fundamental regularities of traditional harmony theory can be restated on a psychophysical basis. For example, in place of the Circle of Fifths, the harmonic "proximity" of tonic, dominant and subdominant chords is expressed by the fact that three semitone steps clockwise or counter-clockwise around the Cycle of Modes (Figure 15a) lead from the tonic to these two "nearest" chords of the same mode. Similarly, the harmonic cadences from the common-practice period that "establish or confirm the tonality and render coherent the formal structure" (Piston, 1987, p. 172) can be described as revolutions of the Cycle of Modes, the total number of semitone steps always being a multiple of three if the cadence is to begin and end in the same mode.

Musical Affect

The curves shown in Figures 11-13 demonstrate that the major chords have an interval structure among all upper partials with a slight predominance of tone triplets with a large lower interval (e.g., 4 semitones) and a small upper interval (e.g., 3 semitones), and vice versa for minor chords. That structural feature alone does not, however, explain why major chords evoke positive emotions in most human listeners and minor chords negative emotions. The question that still remains unanswered is: How can the affective valence of the major and minor modes be explained without recourse to the non-explanation of "cultural habit"? As Sloboda (1976, p. 83) has repeatedly commented: "as psychologists, we need to ask what psychological mechanisms allow these [emotional] meanings to be comprehended by the listener" and "What [musical] structures elicit what emotions, and why?" (Sloboda, 2005, p. 259).

At this point, the Cycle of Modes (Figure 15) can be put to good use. Of the three types of harmonies that do not entail interval dissonance, the tension chords are affectively neutral, inherently ambiguous, non-modal triads. From that starting point, progression to the affect of major or minor harmonies can be achieved directly by a semitone shift down or up. Pitch rises from affective ambiguity imply the negative affect of the minor mode and pitch decreases imply the positive affect of the major mode. Of course, multiple pitch rises and falls can move any triad from one mode to any other mode, but the nearest "local" phenomena in triadic pitch space from a stance of neutrality to one of emotionality are steps around the Cycle of Modes beginning with a tension chord. The simplest formulation of the old puzzle of modality is therefore to ask why the human ear attaches emotional significance to such changes in auditory frequency?

The answer to this question is in fact well known and referred to as the "frequency code" (or the "sound symbolism") of animal calls. Briefly, there is a cross-species tendency for animals to signal their strength, aggression and territorial dominance using vocalizations with a low and/or falling pitch and, conversely, to signal weakness, defeat and submission using a high and/or rising pitch (Morton, 1977). Concrete examples of the frequency code are familiar to most people from the low-pitched growling of aggressive dogs and the high-pitched yelp of injured or retreating dogs, but it is said to be true for species as diverse as primates and birds.

Ohala (1983, 1984, 1994) has been one of the leading advocates of the idea concerning the inherent "sound symbolism" of rising or falling pitch. He has noted that:

> "Animals in competition for some resource attempt to intimidate their opponent by, among other things, trying to appear as large as possible (because the larger individuals would have an advantage if, as a last resort, the matter had to be settled by actual combat). Size (or apparent size) is primarily conveyed by visual means, e.g. erecting the hair or feathers and other appendages (ears, tail feathers, wings), so that the signaler subtends a larger angle in the receiver's visual field. There are many familiar examples of this: threatening dogs erect the hair on their backs and raise their ears and tails, cats arch their backs, birds extend their wings and fan out their tail feathers. [...] As Morton (1977) points out, however, the F0 of voice can also indirectly convey an impression of the size of the signaler, since F0, other things being equal, is inversely related to the mass of the vibrating membrane (vocal cords in mammals, syrinx in birds), which, in turn, is correlated with overall body mass. Also, the more massive the vibrating membrane, the more likely it is that secondary vibrations could arise, thus giving rise to an irregular or "rough" voice quality. To give the impression of being large and dangerous, then, an antagonist should produce a vocalization as rough and as low in F0 as possible. On the other hand, to seem small and non-threatening a vocalization which is tone-like and high in F0 is called for. [...]. Morton's (1977) analysis, then, has the advantage that it provides the same motivational basis for the form of these vocalizations as had previously been given to elements of visual displays, i.e. that they convey an impression of the size of the signaler. I will henceforth call this cross-species F0-function correlation "the frequency code" (Ohala, 1994, p. 330).

A perceptible increase or decrease in pitch signifies a change in the vocalizing animal's assumed social position. There are of course a host of other physiological factors involved, but the "frequency code" is concerned with changes in fundamental frequency of the voice. Other signals have species-specific significance, but it is the rising or falling F0 that has been found to have cross-species generality and profound meaning for any animal within earshot, regardless of night-time obscurity, visual angle or jungle obstructions. A falling F0 implies that the vocalizer is not in retreat, has not backed down from a direct confrontation, may become a physical threat and has assumed a stance of social dominance. Conversely, a rising F0 indicates defeat, weakness, submission, an unwillingness to challenge others, and signals the vocalizer's acknowledgement of non-dominance. How and why these F0 signals have evolved, their correlations with facial expressions and vowel sounds have been amply discussed in the academic literature, but their reality is not in question.

Moreover, the universality of such sound symbolism is known to have spilled over into human languages, where rising and falling intonation have related, if greatly attenuated, meanings concerning social status. Across diverse languages, falling pitch is again used to signal social strength (commands, statements, dominance) and rising pitch to indicate weakness (questions, politeness, deference and submission): "in both speech and music, ascending contours convey uncertainty and uneasiness, and descending contours certainty and stability" (Brown, 2000, p. 289). As argued most forcefully by Ohala (1983, 1984, 1994), the inherent meaning of pitch rises or falls is one of a very small number of cross-linguistic constants of human languages, and demonstrates the importance of our biological roots – extending even to the realm of language [see Morton (1977), Bolinger (1978), Cruttendon (1981), Scherer (1995), Juslin & Laukka (2003), Ladd (1996) and Levelt (1999) for further discussion].

For both animal vocalizations and human speech, the pitch context is provided by the tonic or "natural frequency" of the individual's voice – from which relative increases or decreases can be detected. Since a larger auditory framework, such as musical key, is not needed, the meaning of pitch movement is relative to the tonic – and the "frequency code" can be stated solely as the direction of rising or falling pitch. In the context of diatonic music, however, musical key and the location of the tonic are not "givens", but must be established. Normally, that is done gradually – sometimes with intended ambiguities and delays, but nearly always evolving toward a definite key within which the listener can appreciate the musical significance of any pitch movement. The question then becomes: What is the minimal musical context from which pitch movement will allow the listener to hear unambiguous musical meaning? In diatonic music, the inherent affective meaning of major and minor keys can be established with a resolved harmonic triad. Since a modal triad requires a pitch range of at least 7 semitones, a modally ambiguous triad over a range of 6-10 semitones provides a minimal context from which to establish a major or minor key. It is a simple consequence of the regularities of diatonic harmony that, given the minimal context, a semitone increase can resolve to a minor key and a semitone decrease can resolve to a major key, *but not vice versa*. In general, pitch movement from any three-tone combination that is neither inherently major nor inherently minor shows this same pattern (see Figures 14 and 15, and the Appendix).

Unlike the world of animal vocalizations, key is all-important in music, so that the musical meaning of context-free pitch movement or the musical meaning of isolated intervals is inherently ambiguous. Provided with the necessary minimal context, however, pitch movement has explicit meaning in relation to mode. It is a remarkable fact that the direction of tonal movement from the ambivalence of amodal tension to a major or minor triad is the same as the direction of pitch changes with inherent affect in animal vocalizations and language intonation: *upward pitch movement implies the negative affect of social weakness, downward pitch movement implies the positive affect of social strength*. When a three-tone combination shifts away from the unresolved acoustical tension of intervallic equidistance toward resolution, we infer an affective valence from our detection of the direction of tonal movement: a semitone shift up is weak, a semitone shift down is strong. It is therefore an interesting possibility that the "frequency code" that has been identified in both comparative animal studies and linguistics may be the mechanism that gives affective meaning to diatonic harmony.

The similarity of the binary pattern of affect in response to pitch changes in all three realms (Figure 16) is striking, and suggests an ancient evolutionary history underlying the common perception of major and minor chords. We believe that this may be the key to the puzzle of major and minor affect in diatonic music, but definitive answers must await human brain activation studies. The most obvious prediction is that, aside from whatever patterns of activation are involved in linguistic and musical processing, identical cortical regions will be activated in response to the positive or negative affect of both speech prosody and musical melody.

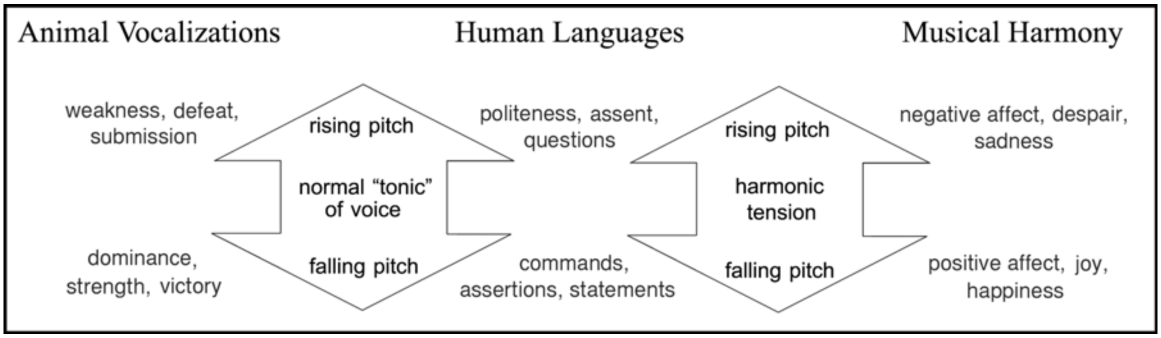

Fig. 16. Sound symbolism in animal calls, language and music. Given an appropriately neutral starting point, rising or falling pitch has analogous affective meaning in all three realms.

ACKNOWLEDGMENTS

The first author would like to thank Professor Eugene Narmour of the University of Pennsylvania for hospitality and stimulating discussions during a Sabbatical year. This research was supported in part by Kansai University's Overseas Research Program for the academic year 2004-2005.

NOTES

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[3] Our thanks go to H. Tanimoto for providing the "bright/dark" data in Figure 9.

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APPENDIX

The generality of three-tone harmonic tension and the remarkable regularity of major and minor resolution in relation to such tension are indicated in Figure A1 and Table A1 below. The Figure shows the complete set of "tension chords" in root position and in 1st and 2nd inversions. Table A1 shows the relationship between the tension chords and chords for which one of the three tones has been shifted up or down by one semitone. It is seen that when a chord with perceptible major or minor quality (major and minor triads, and abbreviated versions of the dominant 7th and minor 7th chords) is produced by such tonal shifts, the chord is, without exception, major when the shift is downward and minor when the shift is upward. This pattern of relationships among the tension, major and minor chords is of course a direct consequence of the known regularities of traditional harmony theory, but is not included in the textbooks since the tension chords are not viewed as a coherent set in traditional harmony theory.

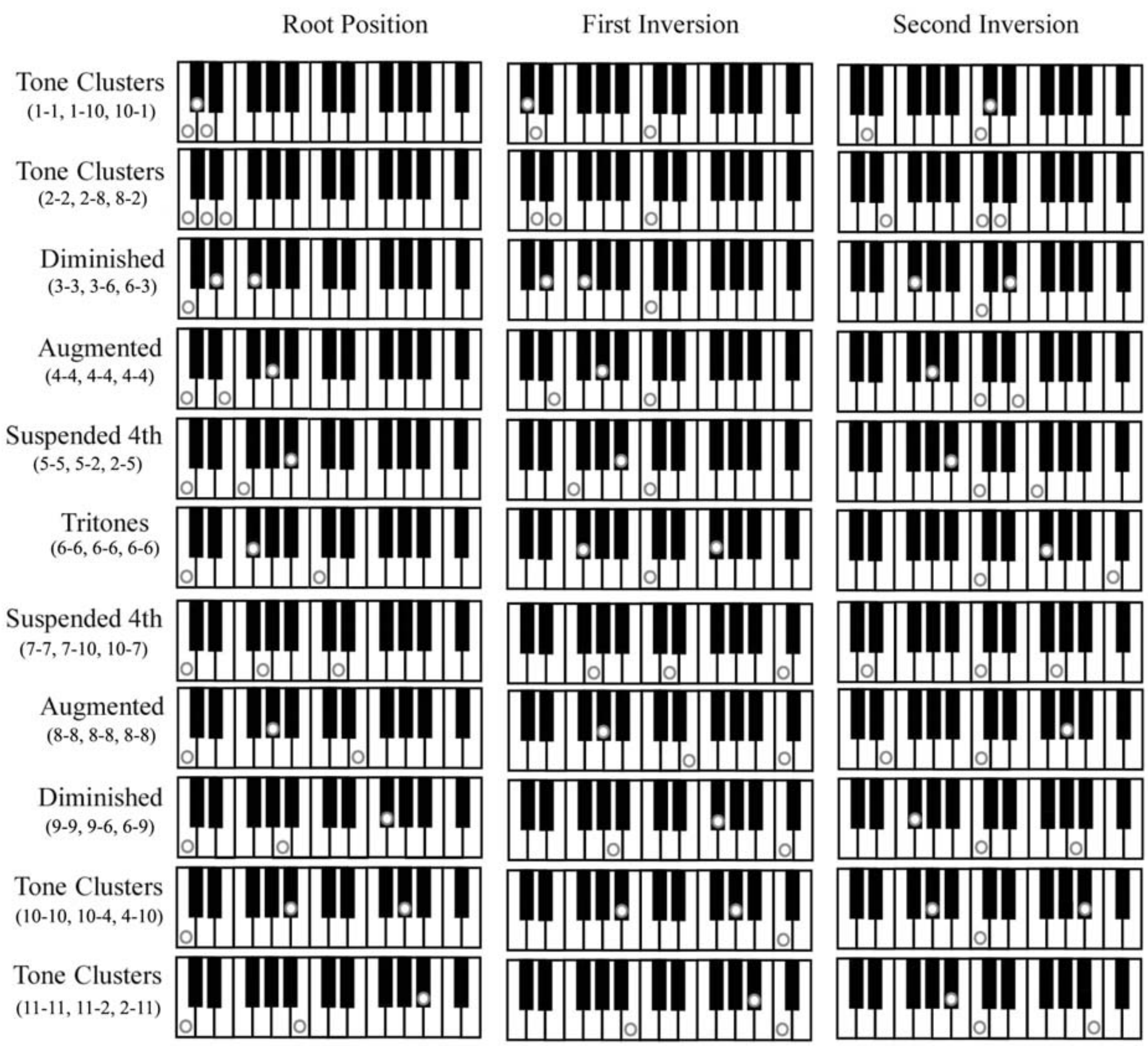

Figure A1: The full set of "tension chords" and their inversions. Interval substructure is indicated below the names of each chord type. Contrary to customary labeling, here the root positions of the "suspended 4th" chords are taken to be those with equivalent intervals (5-5 and 7-7).

The Major and Minor Chords in Relation to the Tension Chords

	Chord after Lowering of One Tone			Tension Chord	Chord after Raising of One Tone		
	n-n-d	n-d-n	d-n-n		n-n-u	n-u-n	u-n-n
Interval Structure (in semitone units, e.g., the major chord in root position is "4-3")	3-2	2-4	4-3	**3-3**	3-4	4-2	2-3
	4-3	3-5	5-4	**4-4**	4-5	5-3	3-4
	5-4	4-6	6-5	**5-5**	5-6	6-4	4-5
	6-5	5-7	7-6	**6-6**	6-7	7-5	5-6
	7-6	6-8	8-7	**7-7**	7-8	8-6	6-7
	5-1	4-3	6-2	(~5-2)	5-3	6-1	4-2
	2-4	1-6	3-5	(~2-5)	2-6	3-4	1-5
	8-7	7-9	9-8	**8-8**	8-9	9-7	7-8
	9-8	8-10	10-9	**9-9**	9-10	10-8	8-9
	3-5	2-7	4-6	(~3-6)	3-7	4-5	2-6
	6-2	5-4	7-3	(~6-3)	6-4	7-2	5-3

	n-n-d	n-d-n	d-n-n		n-n-u	n-u-n	u-n-n
Labels from Music Theory (alternatives are possible)	-	dom7	maj	**dim**	min	-	min7
	maj	maj	maj	**aug**	min	min	min
	maj	dom7	-	**sus4**	-	-	min
	-	-	-	**tritones**	-	-	-
	-	dom7	maj	**sus4**	min	-	-
	-	maj	dom7	(sus4)	min	-	-
		-	maj	(sus4)	-	min	-
	maj	maj	maj	**aug**	min	min	min
	maj	dom7	-	**dim**	-	-	min
	maj	-	dom7	(dim)	min7	min	-
	dom7	maj	-	(dim)	-	-	min

Key: d : Downward semitone shift (from the tension chord) u : Upward semitone shift (from the tension chord)
n : No change (from the initial tension chord) ( ) : Inversions of the tension chords

Table A1: The effects of a semitone shift in any tone of the tension chords (central column). The upper half of the table shows interval structures, the lower half shows the common labels from music theory. Note that, without exception, whenever a semitone shift results in a chord with perceptible major-like quality (the three inversions of the major chord and the five inversions of the dominant seventh chord) or perceptible minor-like quality (the three inversions of the minor chord and two inversions of the minor seventh chord), it is downward movement (the 3 left-hand columns) that produces major chords and upward movement (the 3 right-hand columns) that produces minor chords. It is specifically this pervasive regularity of diatonic harmony that requires a psychological explanation.

Chord	Interval Structure	Experiment (Roberts, 1986)		The Present Model					
				Modality	Dissonance	Tension	Instability	Rank	Sonority
Maj. Root	4-3	1		+3.780	0.504	0.583	0.624	1	
Maj. 1st	3-5	2	I	+2.611	0.641	0.836	0.814	5	I
Maj. 2nd	5-4	3		+3.825	0.498	1.366	0.780	4	
Min. Root	3-4	4		-4.209	0.504	1.158	0.744	2	
Min. 1st	4-5	5	II	-3.075	0.498	1.246	0.756	3	II
Min. 2nd	5-3	6		-2.763	0.641	0.950	0.838	6	
Dim. Root	3-3	7		+0.361	0.764	3.223	1.431	12	
Dim. 1st	3-6	8	III	+0.176	0.695	2.026	1.114	7	III
Dim. 2nd	6-3	9		-0.895	0.695	2.420	1.196	10	
Aug.	4-4	10	IV	+0.384	0.611	6.701	1.998	13	V
Sus. 4th Root	5-2			-0.001	0.715	2.226	1.175	8	
Sus. 4th 1st	2-5			-0.061	0.715	2.438	1.219	11	IV
Sus. 4th 2nd	5-5			-0.304	0.569	3.005	1.191	9	

Table A2: Calculations of the major/minor modality, dissonance, tension and instability of the common triads of diatonic music using Equations 1-7 and upper partials (F0-F5) with amplitudes of 1.0, 0.88, 0.76, 0.64, 0.58, 0.52. The precise ranking is sensitive to model parameters, but consistently gives higher sonority for the major and minor chords and lower sonority for the unresolved chords. Note that the modality scores for major and minor chords are positive and negative, respectively, while the unresolved chords have modality scores near zero. The Roman numerals indicate classes of triads and their relative sonority.