The Perception and Cognition of Pitch Structure in Tonal Music

David Meredith
Department of Computing,
City University, London.
dave@titanmusic.com
www.titanmusic.com

MSc/Postgraduate Diploma in Music Information Technology Lecture
Department of Music, City University, London
Friday, 21 March 2003.

1. Krumhansl's (1990) studies on the perception and cognition of pitch relationships in Western tonal music

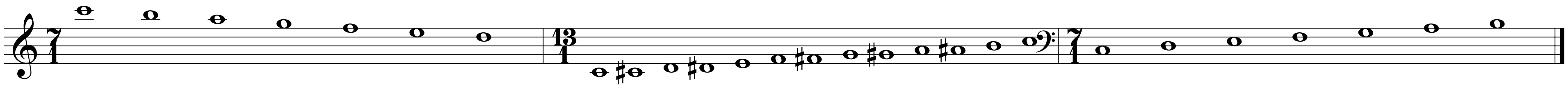
	Tones	*Chords*	*Keys*
Tones	Krumhansl (1990, Chapter 5)	-	-
Chords		Krumhansl *et al.* (1982)	-
Keys	Krumhansl and Shepard (1979) Krumhansl and Kessler (1982)	Krumhansl (1990, Chapter 7)	Krumhansl and Kessler (1982)

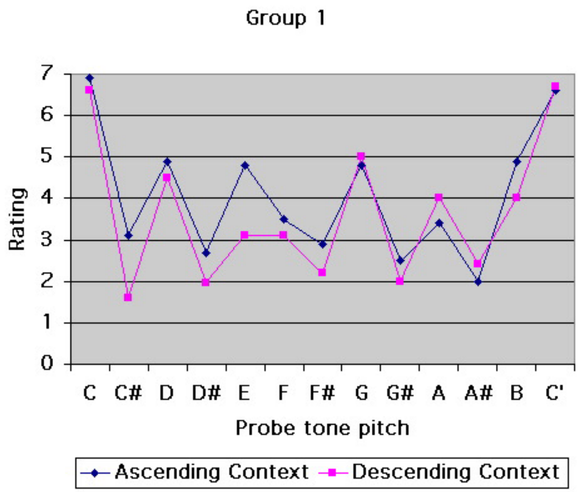
1. Krumhansl's (1990) studies on the perception and cognition of pitch relationships in Western tonal music

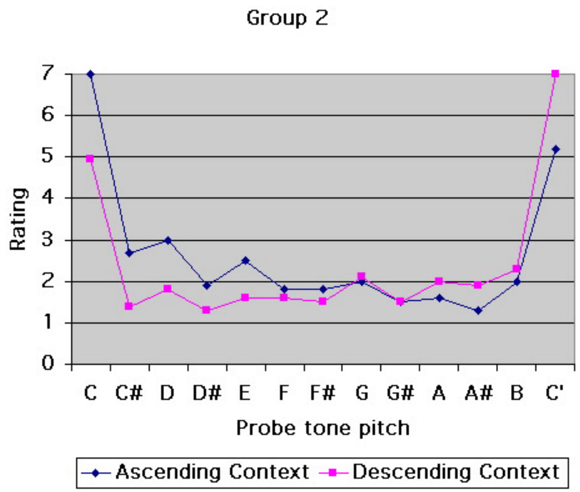
1. In her book, *Cognitive Foundations of Musical Pitch*, Krumhansl (1990) reviews the experimental studies that she had carried out with various collaborators in which she explored the perception of relationships between tones, chords and keys in Western tonal music.
2. The goal of these experiments was to characterize "the listener's internal system for processing pitch structures, focusing primarily on those found in traditional Western music" (Krumhansl, 1990, p. 9).
3. This table shows the type of perceptual relationship studied in each of the experiments that she reviews in her book.
4. Most of these experiments took the form of "probe-tone studies".
5. In a probe-tone study, a listener first hears a standard pattern called the 'context' and then hears a tone called the 'probe-tone'. The listener then has to rate, usually on a scale of 1 to 7, how well the probe-tone fits with the context.

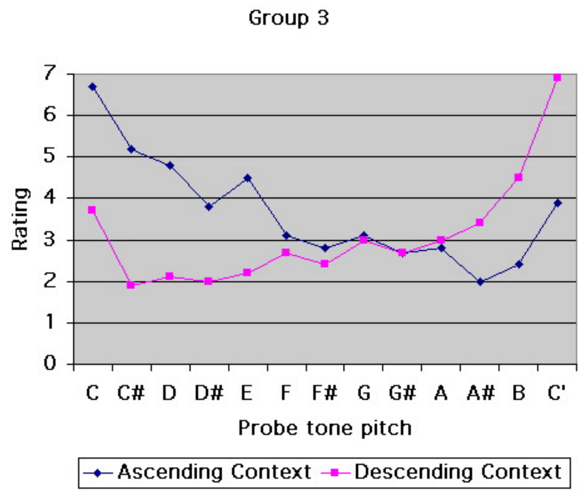
2. Krumhansl and Shepard (1979): Investigating the perceived relationships between tones and keys

Descending context Probe tones Ascending context









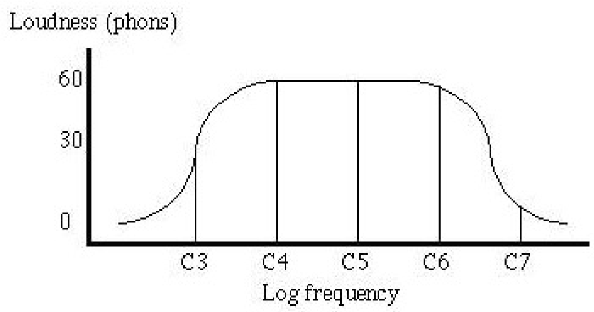
2. Krumhansl and Shepard (1979): Investigating the perceived relationships between tones and keys

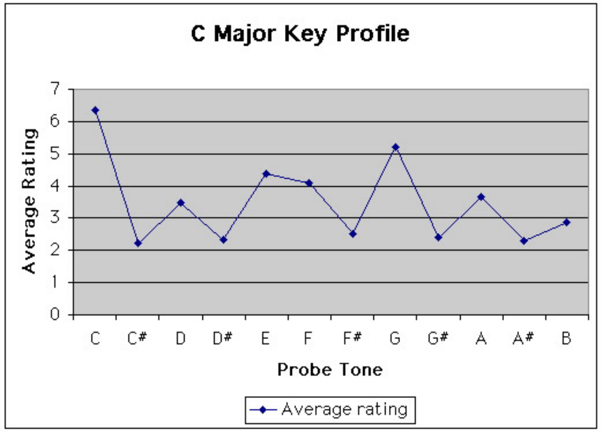
1. The first two experiments to use the probe-tone method were those described by Krumhansl and Shepard (1979).
2. In these experiments, listeners were presented with incomplete ascending or descending C major scales, followed by probe tones with various pitches, and had to judge how well the probe tones completed the scales.
3. In the first experiment, the incomplete descending scale used was this one shown here on the left and the incomplete ascending scale used was the one here on the right.
4. Each probe tone was chosen from the set of 13 tones in the chromatic scale starting on middle C and ending on the C an octave above, as shown here in the middle.
5. In the second experiment, Krumhansl and Shepard (1979) added the quarter tones in between these chromatic scale tones to the set of probe tones used.
6. These graphs summarize the results that they obtained.
7. The graph here on the left shows the results obtained for the musically most experienced subjects who had had an average of 7.4 years of musical training; the middle graph shows the results obtained for subjects with around 5.5 years of musical training; and the bottom graph shows the results obtained for subjects with less than a year of musical training.
8. For the most highly trained subjects,
   (a) the results obtained for the ascending context were very similar to those obtained for the descending context;
   (b) the two tonic tones received the highest rating and both tones received an approximately equal rating; and
   (c) the tones in the C major scale received a higher rating than the tones outside the C major scale.
9. For the group with a moderate amount of musical training,
   (a) again, the ratings for the tonic tones were a lot higher than the ratings for the other tones but the rating for the tonic furthest away from the context was lower than that for the tonic nearest in pitch to the context;
   (b) apart from the tonic tones, there was a gradual decrease in the rating as the tones became more and more distant in pitch from the last tone of the context; and
   (c) again, the scale tones received higher ratings than the non-scale tones but this time the difference between the ratings for the scale tones and those for the non-scale tones were not as great as for the most experienced subjects.
10. For the group of subjects with the least training,

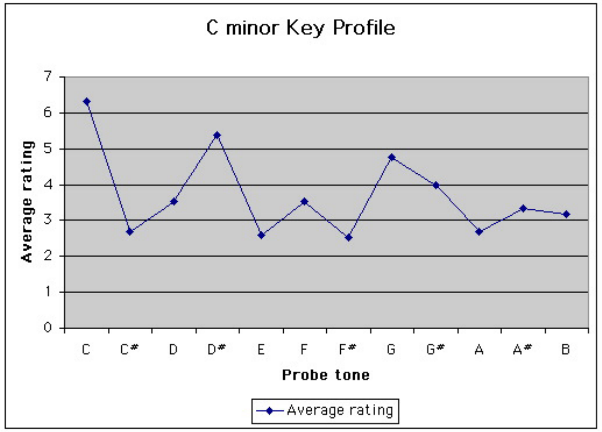
(a) tones further away from the end of the context were generally rated lower;
(b) the tonic furthest from the context was rated higher than would be predicted by its distance from the context, but not as much higher as it was by the subjects with more training; and
(c) scale-tones were not rated significantly more highly than non-scale tones.

11. These results suggest that, with training, Western listeners acquire what Krumhansl calls a *tonal hierarchy* in which one tone, the tonic, is judged to be most stable, while the other scale-tones are judged less stable but more stable than those tones outside of the scale.

3. Krumhansl and Kessler (1982): Investigating the relationships between tones and keys







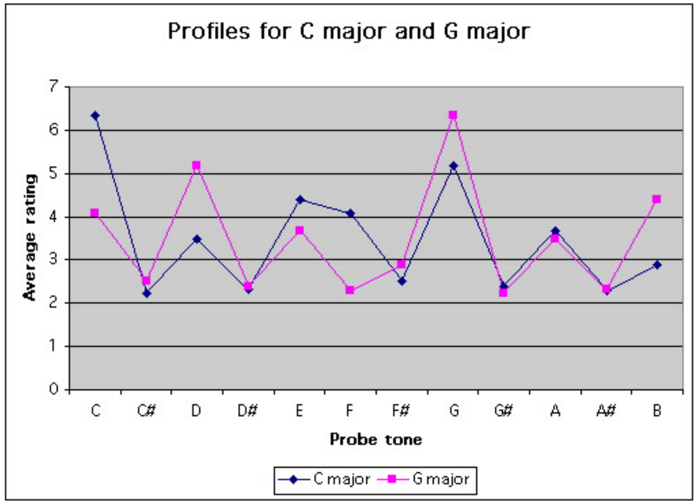
- Used various different major and minor key-defining contexts.
- Used various different tonics.
- Subjects given practice trials and told to make full use of rating scale.
- Subjects made multiple judgements of the same context-probe-tone combination.
- Only subjects with at least 5 years of musical training used.
- Used circular tones to eliminate effect of pitch distance.
- Subjects asked to judge fittingness rather than completion.

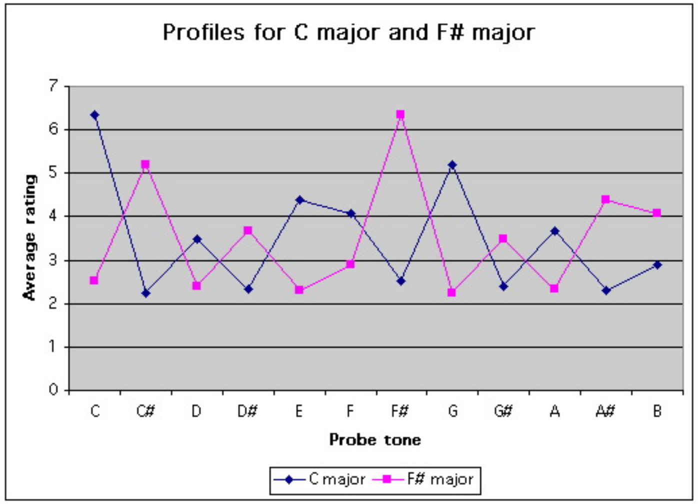
3. Krumhansl and Kessler (1982): Investigating the relationships between tones and keys

1. Krumhansl and Kessler (1982) replicated and extended the experiments of Krumhansl and Shepard (1979).
2. Krumhansl and Kessler (1982) used various different key-defining contexts to test the hypothesis that any strongly key-defining context will give rise to similar probe-tone ratings.
3. Used major and minor key contexts.
4. Used various different tonics to test the hypothesis that a similarly shaped tonal hierarchy would be obtained for any tonic.
5. Used a more careful experimental procedure in which the subjects were given some practice trials before starting the experiment proper, and instructed to use the full range of the rating scale.
6. The trials were arranged in blocks so that listeners made multiple judgements for each probe-tone-context combination. Within each block, the order of the trials was randomized. The order of the blocks was randomly selected for each subject.
7. To eliminate the possibility of subjects adopting an intentionally unmusical strategy in their responses (which might have been the case for the non-musicians in the experiments of Krumhansl and Shepard (1979)), only subjects with at least 5 years of formal musical training were chosen.
8. Krumhansl and Shepard (1979) had used flute tones and sine waves, both of which have very definite qualities of tone *height*. That is, given two flute tones or two sine waves that are a semitone or more apart, two subjects will generally agree about whether the first tone is higher than the second or vice-versa.
9. It was clear from the results of Krumhansl and Shepard's (1979) experiments that listeners with less musical training tended to give lower ratings to tones that were further away from the context.
10. Krumhansl and Kessler (1982) attempted to eliminate the effect of pitch distance by using special tones called 'circular tones' that are not perceived to have any definite sense of pitch height.
11. Each of the circular tones use by Krumhansl and Kessler (1982) contained five sine-wave components, each one an octave above the next, the amplitudes of these components being fixed so that the spectrum of the tone had a bell-shape as shown here.
12. Because the highest and lowest components of these tones have very low amplitudes, the tones have an organ-like quality with no well-defined lowest or highest pitch and approximately the same overall pitch height.
13. You'll hear a lot of these tones later on so I won't play you any just now.
14. One other difference between the experiments of Krumhansl and Kessler (1982) and those of Krumhansl and Shepard (1979) was that the contexts used by Krumhansl and Kessler (1982) sounded complete and the subjects were asked to judge how well the probe-tones fit with the context, rather than how well the probe-tones *completed* the context.

15. The results of the experiment showed that the subjects agreed very well with each other and gave similar responses each time a particular context-probe-tone combination was heard.
16. They also found that essentially the same shape of profile was obtained for all major keys and a different profile was obtained for all the minor keys.
17. They also found that essentially the same responses were obtained regardless of the specific key-defining context used.
18. The graph here on the left shows the rating profile obtained for the major key context and the graph here on the right shows the profile obtained for the minor key context. Both graphs are drawn as though the tonic is C.
19. For the major key context,
    (a) the highest rating was given to the tonic;
    (b) the next highest rating was given to the dominant;
    (c) followed by the mediant;
    (d) then the other scale tones; and finally
    (e) the non-scale tones.
20. For the minor key context,
    (a) the highest rating again given to the tonic;
    (b) followed by the mediant and the dominant;
    (c) then the other scale degrees; and finally
    (d) the non-scale degrees.

4. Krumhansl and Kessler (1982): Measuring the perceptual distance between keys





f# d bb

Db/C# A F Db/C#

c# a f

E C Ab

g# e c

B G Eb

eb/d# b g eb/d#

F# D Bb

f# d bb

4. Krumhansl and Kessler (1982): Measuring the perceptual distance between keys

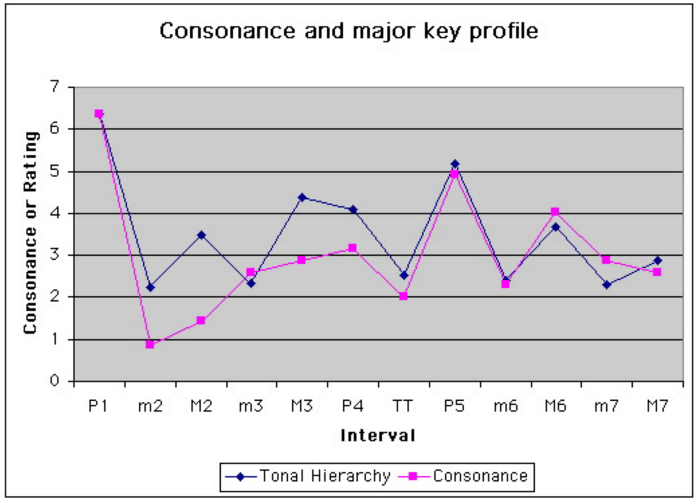
1. Each of the probe-tone rating profiles or 'tonal hierarchies' obtained by Krumhansl and Kessler (1982) describes the perceived pattern of stability imposed on the tones within an octave by a particular key.
2. In tonal music theory, modulations generally occur between keys that are considered 'closely related'.
3. In general, a major key is considered to be closely related to the major key of its dominant, the major key of its sub-dominant, its relative minor and its tonic minor.
4. While a minor key is considered to be closely related to the major or minor key of its dominant and subdominant, and its relative and tonic major keys.
5. Krumhansl and Kessler (1982) proposed that the perceived relatedness of two keys could be predicted by measuring the similarity of their probe-tone rating profiles.
6. On the previous slide I showed you the probe-tone rating profiles for C major and C minor. The probe-tone rating profiles for the other keys are the same shape as these profiles except that they begin on different pitch classes. For example, the rating profile for G major would be equal to the profile for C major shifted along by seven semitones, as shown in this graph here on the left.
7. As you can see from this graph, the rating profiles of C major and G major are quite similar—they generally go up and down in the same places.
8. On the other hand, this graph shows the rating profiles of C major and F♯ major which are quite different, as you can see—where one profile goes up, the other tends to go down.
9. One standard statistical measure of the degree of similarity between two sets of data is called the correlation.
10. The correlation between two sets of data is a value between -1 and 1. A correlation of 1 means that the two sets of data are exactly the same, and a correlatino of -1 means that they are exactly opposite.
11. The correlation between the C major profile and the G major profile is .651 which is a fairly high value.
12. The correlation between the C major profile and the F♯ major profile is -.683 indicating a fairly high anti-correlation.
13. After finding the correlation between every pair of keys, Krumhansl and Kessler (1982) used a technique called *multidimensional scaling* to get a spatial representation in which each key is represented as a point and the correlation between any two keys is represented by the distance between the two points representing the keys.
14. They found that they could only represent the correlation between the keys in this way if they used a four-dimensional Euclidean space, that is, a space in which the distance between any two points is measured in a straight line.

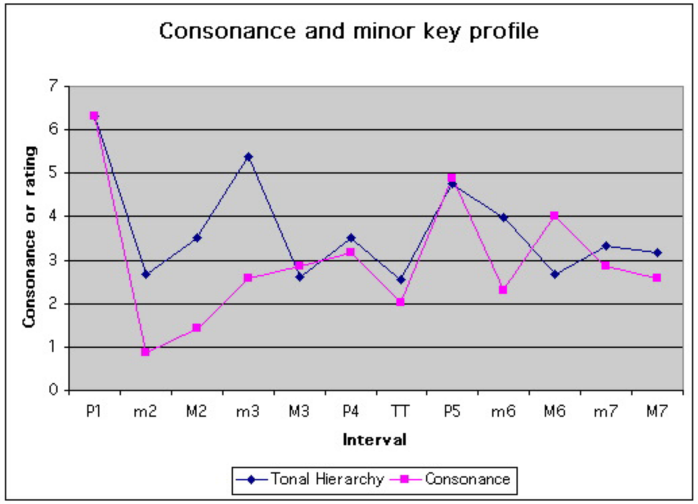
15. However, they found that if they used a curved space in which the inter-key distances were measured within the curved surface of a torus they could represent the inter-key distances in three dimensions.

16. This diagram here gives a visual representation of the correlations between the keys. In this diagram, the torus has been cut along both of its circumferences and unfolded. [Demonstrate with piece of paper.]

17. Note that in this multidimensional scaling solution to the results of their experiment, the circle of fifths emerges as a 'straight line' within the surface of the torus and the relative major/relative minor pairs are also close to each-other.

5. Correlation between tonal hierarchies and tonal consonance



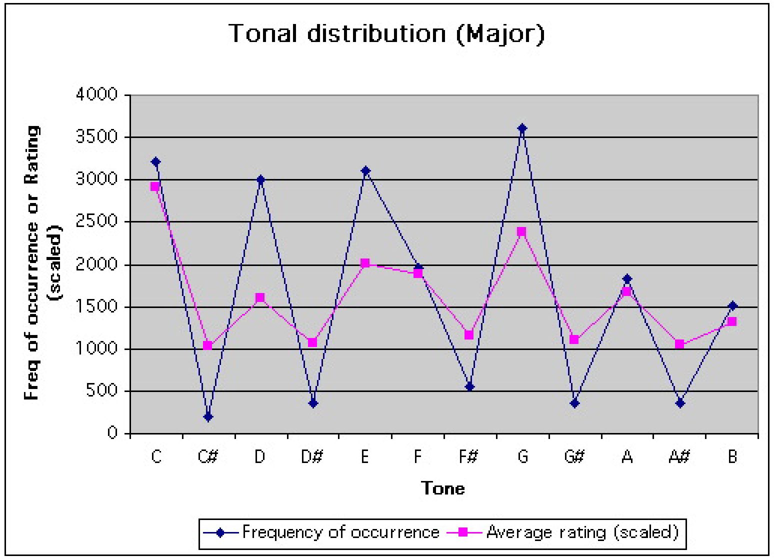


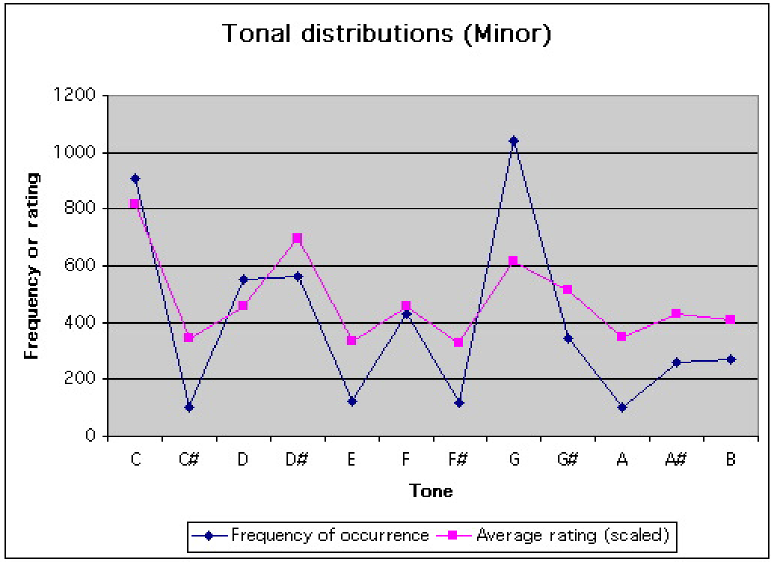
- *Tonal consonance:* Psychophysical phenomenon in which two tones sounding simultaneously sound 'fused', 'smooth', harmonious or 'pleasing'.
- *Musical consonance:* Two tones sounding simultaneously interpreted to be stable in a particular musical style.
- Various different measures of tonal consonance proposed (e.g., Helmholtz, 1954; Kameoka and Kuriyagawa, 1969; Malmberg, 1918)
- Quite high correlation between major key profile and Helmholtz's (1954) measures of consonance.
- Lower, but still statistically significant correlation between minor key profile and consonance measure of Kameoka and Kuriyagawa (1969).

5. Correlation between tonal hierarchies and tonal consonance

1. It's important to distinguish between *tonal consonance* and *musical consonance*.
2. The degree of tonal consonance of a pair of tones sounding together is supposed to be a measure of how much they fuse into a single percept or how harmonious they sound.
3. On the other hand, the musical consonance of a given pair of tones sounding simultaneously is determined by how stable they are interpreted to be in a particular musical style.
4. Thus, for example, the perfect fourth is considered musically dissonant in a tonal context when heard between the lowest part and a higher one.
5. However, according to most measures of tonal consonance, the perfect fourth is a highly consonant interval.
6. So, although there is obviously some connection between tonal consonance and the intervals that have evolved to be musically consonant in certain musical styles, there is no direct equivalence between the two forms of consonance.
7. Various different measures of tonal consonance have been proposed since the 12th century. The most well-known is probably the hypothesis that tones whose fundamentals frequencies are separated by low-integer ratios are heard to be consonant, the higher the integers involved in the ratio, the more dissonant the interval is heard to be. This measure was originally proposed by Pythagoras.
8. Helmholtz (1954) noticed that when two tones are close but not identical in pitch, a sensation of beating or roughness is heard.
9. More modern studies (see Rasch and Plomp, 1999, pp. 106–108) explain this sensation of roughness by claiming that when the sine wave components of complex tones are close enough together, they 'interfere' with each other by stimulating the same area of the basilar membrane. This occurs when two sine-wave components are within what is called one 'critical bandwidth' of each other.
10. Krumhansl (1990, pp. 55–62) calculated the correlations between the tonal hierarchies and various different tonal consonance measures.
11. She found that there was a statistically significant correlation between the major key probe-tone profile and a number of different measures of tonal consonance; and a somewhat lower, but still significant correlation between the minor key probe-tone profile and one particular measure of tonal consonance given by Kameoka and Kuriyagawa (1969).
12. These two graphs show the consonance measures of Kameoka and Kuriyagawa (1969) plotted against the average probe-tone ratings obtained by Krumhansl and Kessler (1982).
13. You can see from these graphs that the correlation between consonance and the major key profile is considerably better than that between consonance and the minor key profile.

6. Correlation between tonal hierarchies and statistical distribution of tones in tonal works



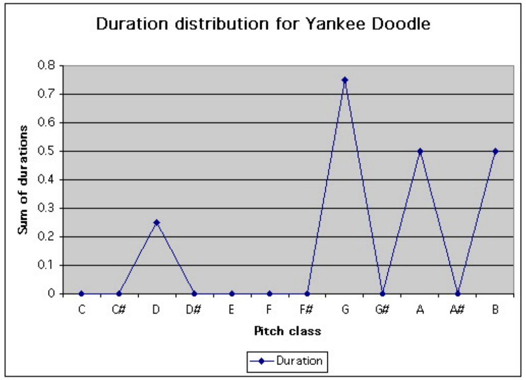


- Youngblood (1958) and Knopoff and Hutchinson (1983) measured distribution of tones in songs and other vocal works by Schubert and others.
- Krumhansl (1990) found very high correlations between frequency distributions of tones in these works and key profiles.

6. Correlation between tonal hierarchies and statistical distribution of tones in tonal works

1. Youngblood (1958) and Knopoff and Hutchinson (1983) measured the frequency of occurrence of each of the 12 chromatic scale tones in various songs and other vocal works by Schubert, Mendelssohn, Schumann, Mozart, Richard Strauss and J. A. Hasse.
2. The graph on the left here shows the frequencies of occurrence of tones in major key works and the graph on the right shows the frequencies of occurrence of tones in minor key works.
3. The correlation between the major key profile and the distribution of tones in major works is considerably higher than the correlation between tonal consonance and the major key profile (and similarly for the minor key profile).

7. Krumhansl and Schmuckler's (1990) key-finding algorithm

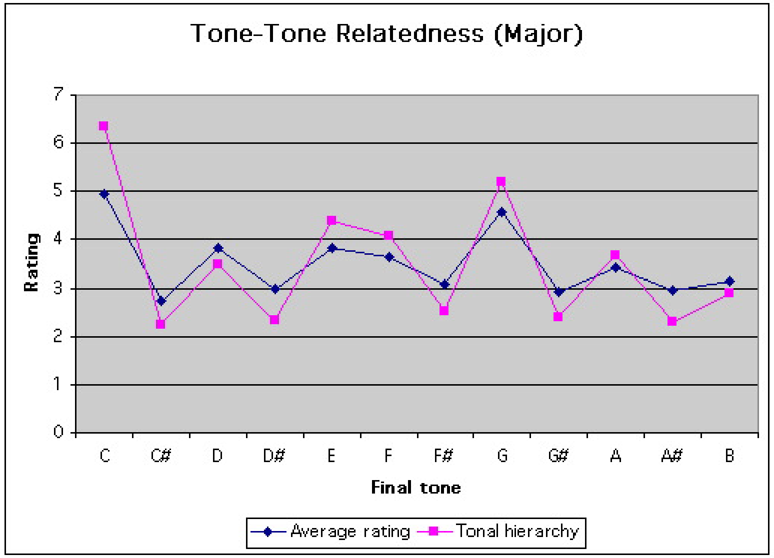


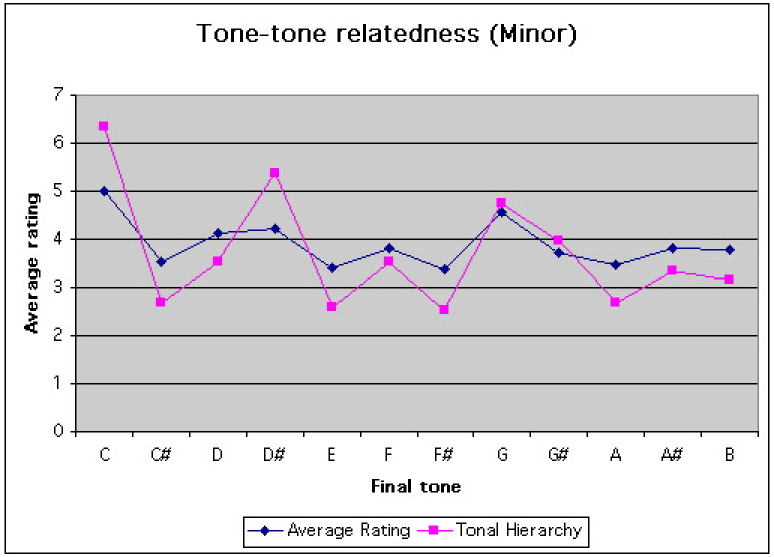
Key	Score	Key	Score
C major	0.274	C minor	-0.013
C sharp major	-0.559	C sharp minor	-0.332
D major	0.543	D minor	0.149
E flat major	-0.130	E flat minor	-0.398
E major	-0.001	E minor	0.447
F major	0.003	F minor	-0.431
F sharp major	-0.381	F sharp minor	0.012
G major	0.777	G minor	0.443
A flat major	-0.487	A flat minor	-0.106
A major	0.177	A minor	0.251
B flat major	-0.146	B flat minor	-0.513
B major	-0.069	B minor	0.491

7. Krumhansl and Schmuckler's (1990) key-finding algorithm

1. Krumhansl (1990, p. 77) takes the strong correlation between the frequency distribution of tones in tonal works and the probe-tone key-profiles to suggest that "the tonal hierarchies might be acquired through experience with the musical style, particularly through internalizing the relative frequencies and durations with which tones are sounded".
2. Krumhansl and Schmuckler (1990) propose a key-finding algorithm based on tonal hierarchies.
3. This algorithm takes a representation as input that gives the duration and chromatic pitch (i.e., MIDI note number) of each note in the passage and generates as output a prediction of the key that the passage will be perceived to be in.
4. The first step in the algorithm is to count up for each different pitch class the sum of the durations of tones with that pitch class in the passage.
5. For example, if we take opening bar of 'Yankee Doodle', as shown here, we find that
   (a) the sum of the durations of the G naturals gives .75 of a minim,
   (b) the durations of the B naturals add up to half a minim,
   (c) the durations of the A naturals add up to half a minim
   (d) and there is one quaver D natural.
6. We can then draw a graph showing the durations of the various pitch classes within the passage being analysed, as shown here.
7. The next step in the algorithm is to calculate the correlation between this graph and each of the 24 major and minor key profiles. This table here shows the correlation between this graph showing the durations of the various pitches in the 'Yankee Doodle' excerpt and each of the major and minor key profiles.
8. The algorithm then predicts that the perceived key will be the one whose profile best correlates with the graph showing the distribution of tone durations for the passage.
9. So in this case, the algorithm correctly predicts that the key of 'Yankee Doodle' is G major.
10. Krumhansl (1990, p. 84) applied the algorithm to the first four tones of each of the Preludes in Bach's *Das Wohltemperirte Klavier* and found that in each case, the notated key correlated significantly with the distribution of tones in the first four notes.
11. Cohen's (1977) carried out an experiment in which musicians were asked to identify the key of a prelude after hearing just the first four tones and Krumhansl (1990) found that the algorithm performed better than the subjects in Cohen's (1977) experiment.

8. Krumhansl (1990, Chapter 5): Perceived relations between tones





8. Krumhansl (1990, Chapter 5): Perceived relations between tones

1. To investigate the perceived relationships between tones, Krumhansl used a variant of the probe-tone method.
2. In this experiment, subjects were presented with trials in which they first heard a strong key-defining context followed by two tones, played in succession forming a melodic interval. In each trial, the subject had to rate on a scale of 1 to 7 how well the second tone followed the first in the given context.
3. The graph on the left shows the average rating obtained for each final pitch when preceded by a major key defining context together with the major key profile. As you can see, both graphs go up and down in roughly the same places and in fact the correlation between them is .97 which is very high indeed.
4. The graph on the right shows the average rating obtained for each final pitch when preceded by a minor key defining context together with the minor key profile. The correlation is .92 which is only slightly less than that for the major key contexts.
5. This shows that listeners like to hear intervals that end on tones which have high ratings in the tonal hierarchy of the preceding context.
6. This reinforces the interpretation that the probe-tone ratings obtained in the Krumhansl and Kessler (1982) experiments can be interpreted as being a measure of stability or finality.

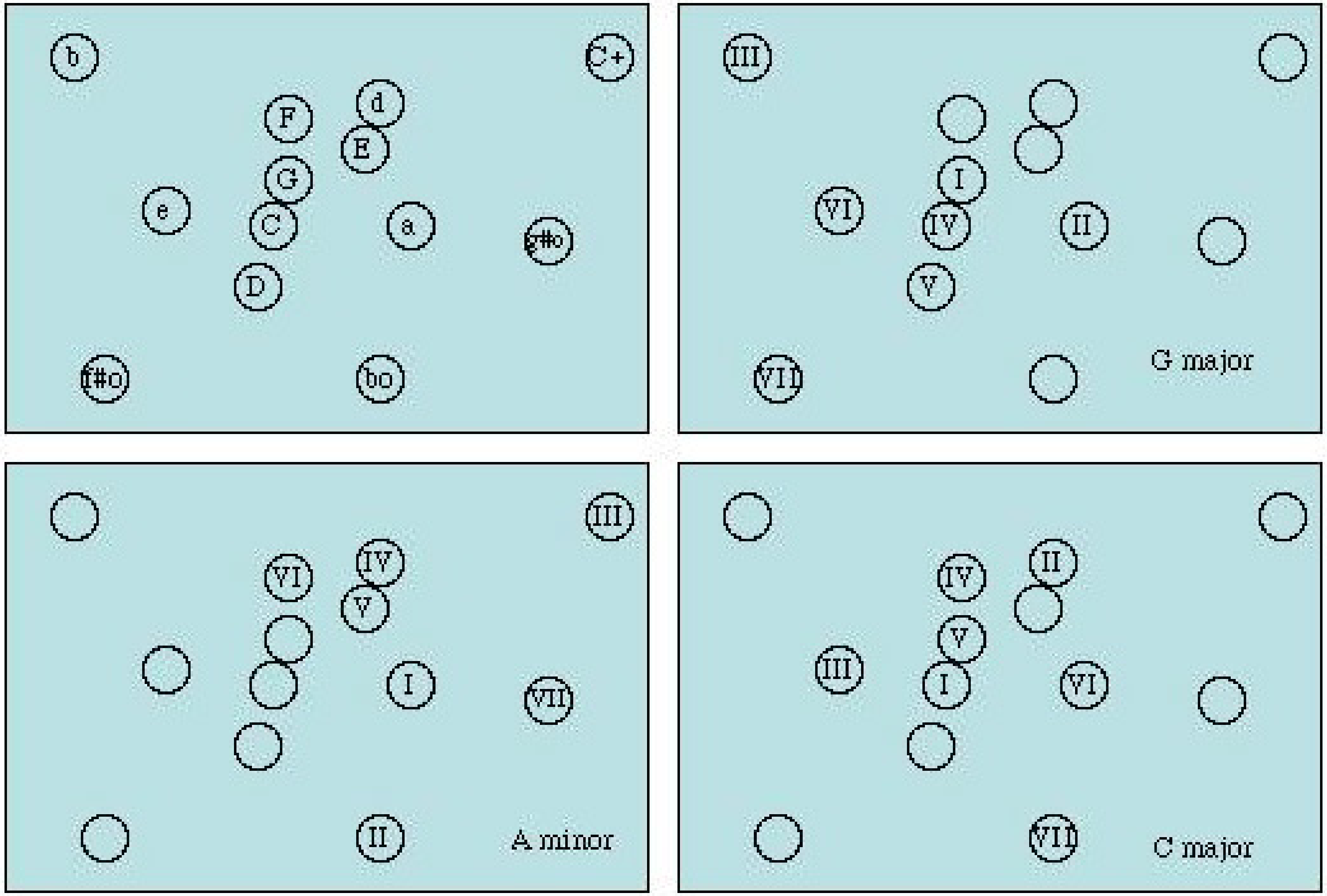
9. Krumhansl (1990, Chapter 7): Perceived relations between chords and keys

- Subjects generally gave higher ratings to major triads than minor triads and higher ratings to minor triads than diminished triads.
- Subjects gave higher ratings to chords that function as basic harmonic elements in the context key.
- Subjects gave higher ratings to chords containing tones that have high ratings in the tonal hierarchy.
- By far the best predictor of the ratings given to the fittingness of chords was the ratings of the component tones of the chords in the tonal hierarchy for the key.

9. Krumhansl (1990, Chapter 7): Perceived relations between chords and keys

1. Krumhansl (1990, Chapter 7) describes two probe-tone-like experiments that she carried out in order to investigate the perceived relatedness between triads and keys.
2. In each trial of the first experiment, subjects were presented with a context consisting of a rising and falling major or minor scale which was then followed by a major, minor or diminished triad. The subjects had to rate how well the triad fit with the preceding context.
3. In the second experiment, the context was changed to a chord progression containing all the chords in the key being defined, ordered along the circle of fifths.
4. The results obtained were very similar for both contexts.
5. Krumhansl (1990, p. 177) derived the following conclusions from analysing the results of these experiments:
   (a) Subjects generally gave higher ratings to major triads than minor triads and higher ratings to minor triads than diminished triads.
   (b) Subjects gave higher ratings to chords that function as basic harmonic elements in the context key.
   (c) Subjects gave higher ratings to chords containing tones that have high ratings in the tonal hierarchy.
   (d) By far the best predictor of the ratings given to the fittingness of chords was the ratings of the component tones of the chords in the tonal hierarchy for the key.

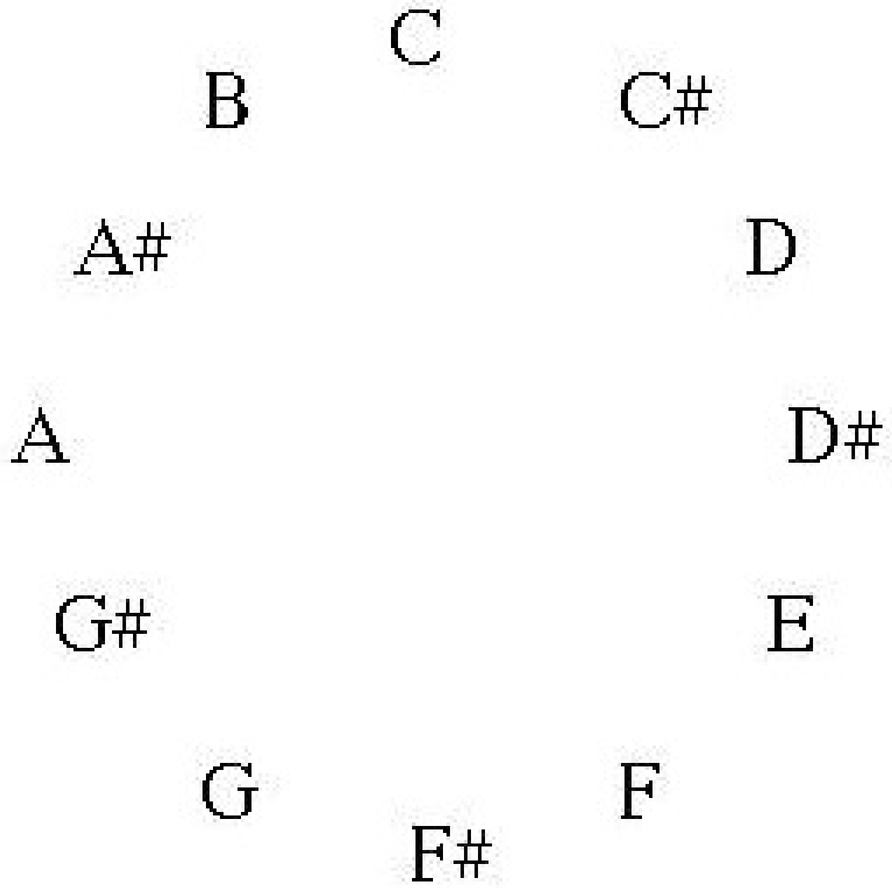
10. Krumhansl *et al.* (1982): The perceived relations between chords within keys



10. Krumhansl *et al.* (1982): The perceived relations between chords within keys

1. Krumhansl *et al.* (1982) carried out an experiment to explore the perceived relatedness between chords in a tonal context.
2. In each trial of the experiment, the listeners were first presented with a key-defining context consisting of a rising scale in either C major, A minor or G major. This was then followed by two chords, each taken from one of the three keys. Listeners had to judge how well the second chord followed the first in the context of the scale sounded at the beginning of each trial.
3. The ratings did not depend in a regular way on the key of the context.
4. They used the multidimensional scaling technique to derive a spatial representation in which chords rated more similar to each other were positioned more closely together in the space. The result is shown here at the top and then repeated three times below to show the positions of the chords within particular keys.
5. Note that the chords in G major emerged on the left-hand side of the space, while the chords of C major emerged in the middle and those in A minor emerged on the right-hand side.
6. So the experiment showed that chords in the same key are perceived as being more closely related than chords in different keys.
7. The fact that the results were independent of the context that began each trial suggested that the perceived distance between chords is essentially independent of the tonal context.
8. This result was confirmed in a later experiment by Bharucha and Krumhansl (1983) which showed that chords in different keys are perceived to be less related even in the absence of any key-defining context.

11. The Tritone Paradox (Deutsch, 1995, Tracks 14–18)



11. The Tritone Paradox (Deutsch, 1995, Tracks 14–18)

1. In the second part of this lecture we're going to do an experiment on a strange auditory phenomenon known as the tritone paradox (Deutsch, 1987; Deutsch *et al.*, 1987).
2. The basic pattern that produces the tritone paradox consists of two circular tones a half octave apart [Play on piano].
3. The strange thing about this pattern is that when you play one tone of the pair, followed by the other, some people will hear it as an ascending interval and others will hear it as a descending interval.
4. Even experienced musicians disagree over whether a given pattern is ascending or descending.
5. Now we know that in general, when a melody is transposed to another key, the perceived relations between the tones don't change—we can still recognize the transposed version of the melody as being 'the same as' the untransposed version.
6. However, whether you hear the tritone paradox pattern as ascending or descending depends upon exactly what pitch level it is played at. At some pitch levels you will hear it as ascending, like this [PLAY ON PIANO] but at other pitch levels you will hear it as descending, like this.
7. Because the tones used to construct the tritone paradox pattern are circular tones, their pitch height is very ambiguous and this is essential to the paradoxical effect.
8. A tone's pitch can be decomposed into two components: its pitch height and its pitch class. The pitch class of a tone contains the tone and all the tones an integer number of octaves away from it. For example, the pitch class of middle C contains all Cs in all octaves.
9. We can denote a pitch class by giving simply the pitch name of the note without its octave number. Thus, the pitch class C contains all Cs, the pitch class C♯ contains all C♯s and D♭s and so on. Note that we are assuming enharmonic equivalence here.
10. We can arrange the pitch classes so that they are all one semitone away from their neighbours giving the so called 'pitch class circle' which is shown here.
11. To explain the tritone paradox, Deutsch (1995) hypothesized that each of us has this chroma circle encoded in some way in our minds and that it has a particular up-and-down orientation in each of us.
12. That is, one person may have it encoded so that the C is at the top as shown here, while another person may have it encoded so that the F♯ is at the top or some other pitch class.
13. Deutsch (1995) then hypothesized that whether or not we hear a given tritone as ascending or descending can be predicted by whether it ascends or descends in this diagrammatic representation of the chroma circle when the circle is orientated in the way that it is orientated in our minds. [GIVE EXAMPLES].

14. In the experiment that we're all about to do, you will hear lots of tritones at various different pitches and you have to judge for each one whether you hear it as ascending or descending.
15. We then plot the proportion of times that an individual hears a given tritone as descending against the first tone in the tritone and we get a graph like the one shown here.
16. When Deutsch carried out the experiment, she confirmed that when the tritone began on tones in one half of the pitch-class circle, they were heard as ascending but when they began on tones in the other half of the pitch class circle, they were heard as descending.
17. Another result of the experiment was that the orientation of chroma circle varied strikingly from one individual to another. For example, for one individual the chroma circle was orientated with G♯ and A at the top, whereas another individual's chroma circle was orientated with C♯ and D at the top.
18. This result suggests that we all have some kind of sensitivity to the absolute pitch of tones, even though most of us cannot name any tone that we hear.
19. Another interesting aspect of the phenomenon is that there seems to be some kind of correlation between the way that the pitch class circle is orientated in an individual and the native language and accent of the individual.
20. Moreover, people who have had a lot of experience at speaking lots of different languages seem to have a less definite orientation than those who have spoken the same language with the same accent all their life.
21. As we have a variety of different nationalities in this group, I thought it would be interesting to test the effect of language on the perception of the tritone paradox by repeating Deutsch's experiment now.
22. So, to start with, if you could all fill in the section at the bottom of the answer sheet.
23. In this experiment you're going to hear lots of tritones and all you have to do for each one is record whether you heard it as ascending or descending.
24. The tritones will be presented in 16 groups of 12, each group separated from the next by a gap of 30s.
25. Each box in the table at the top of the answer sheet corresponds to a different tritone.
26. If you hear a tritone as ascending then you put an upwards pointing arrow in the box for that tritone; and if you hear it as descending, then you put a downard pointing arrow in the box.
27. As you listen to the tritones, you work down each column from the top to the bottom before moving onto the next group. So for the first tritone, you indicate whether you hear at as ascending or descending by putting an arrow in the top left box, then for the second tritone you put an arrow in the second box down in the first column, then the third box in the first column and so on.

References

Bharucha, J. J. and Krumhansl, C. L. (1983). The representation of harmonic structure in music: Hierarchies of stability as a function of context. *Cognition*, **13**, 63–102. Cited by Cross *et al.* (1991) and Krumhansl (1990).

Cohen, A. J. (1977). Tonality and perception: Musical scales prompted by excerpts from *Das Wohltemperirte Clavier* of J. S. Bach. In *Proceedings of the Second Workshop on Physical and Neuropsychological Foundations of Music*, Ossiach, Austria. Cited by Krumhansl (1990).

Cross, I., West, R., and Howell, P. (1991). Cognitive correlates of tonality. In P. Howell, R. West, and I. Cross, editors, *Representing Musical Structure*, pages 201–243. Academic Press, London.

Deutsch, D. (1987). The tritone paradox: Effects of spectral variables. *Perception and Psychophysics*, **41**, 563–575. Cited by Krumhansl (1990).

Deutsch, D. (1995). Musical illusions and paradoxes. Audio CD, Available from Philomel Records Inc., `http://www.philomel.com`.

Deutsch, D., Kuyper, W. L., and Fisher, Y. (1987). The tritone paradox: Its presence and form of distribution in a general population. *Music Perception*, **5**, 79–92. Cited by Krumhansl (1990).

Dowling, W. J. (1991). Pitch structure. In P. Howell, R. West, and I. Cross, editors, *Representing Musical Structure*, pages 33–57. Academic Press, London.

Helmholtz, H. L. F. (1954). *On the Sensations of Tone as a Physiological Basis for the Theory of Music*. Dover, New York. Translation of Fourth German edition (1877) by Alexander J. Ellis, originally published in 1885. Introduction by Henry Margenau. Cited by Krumhansl (1990).

Kameoka, A. and Kuriyagawa, M. (1969). Consonance theory Part II: Consonance of complex tones and its calculation method. *Journal of the Acoustical Society of America*, **45**, 1460–1469. Cited by Krumhansl (1990).

Knopoff, L. and Hutchinson, W. (1983). Entropy as a measure of style: The influence of sample length. *Journal of Music Theory*, **27**, 75–97. Cited by Krumhansl (1990).

Krumhansl, C. L. (1990). *Cognitive Foundations of Musical Pitch*, volume 17 of *Oxford Psychology Series*. Oxford University Press, New York and Oxford.

Krumhansl, C. L. and Kessler, E. J. (1982). Tracing the dynamic changes in perceived tonal organisation in a spatial representation of musical keys. *Psychological Review*, **89**, 334–368. Cited by Cross *et al.* (1991), Dowling (1991) and Krumhansl (1990).

Krumhansl, C. L. and Shepard, R. N. (1979). Quantification of the hierarchy of tonal functions within a diatonic context. *Journal of Experimental Psychology: Human Perception and Performance*, **5**(4), 579–594. Cited by West *et al.* (1991), Cross *et al.* (1991) and Krumhansl (1990).

Krumhansl, C. L., Bharucha, J. J., and Kessler, E. J. (1982). Perceived harmonic structure of chords in three related musical keys. *Journal of Experimental Psychology: Human Perception and Performance*, **8**, 24–36. Cited by Cross *et al.* (1991) and Krumhansl (1990).

Malmberg, C. F. (1918). The perception of consonance and dissonance. *Psychological Monographs*, **25**(2, (Whole No. 108)), 93–133. Cited by Krumhansl (1990).

Rasch, R. and Plomp, R. (1999). The perception of musical tones. In D. Deutsch, editor, *The Psychology of Music*, pages 89–112. Academic Press, San Diego, second edition.

West, R., Howell, P., and Cross, I. (1991). Musical structure and knowledge representation. In P. Howell, R. West, and I. Cross, editors, *Representing Musical Structure*, pages 1–30. Academic Press, London.

Youngblood, J. E. (1958). Style as information. *Journal of Music Theory*, **2**, 24–35. Cited by Krumhansl (1990).