

# MUSIC PSYCHOLOGY: TONAL STRUCTURES IN PERCEPTION AND MEMORY

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## CONTENTS

INTRODUCTION.....	277
CONSONANCE.....	278
TUNING AND INTONATION.....	280
CATEGORICAL PITCH PERCEPTION .....	281
ABSOLUTE PITCH PERCEPTION.....	283
MODELS OF TONAL RELATIONS .....	285
TONAL HIERARCHIES .....	287
HARMONY AND KEY .....	290
CODING MODELS OF MUSIC.....	291
LINGUISTIC THEORY APPLIED TO MUSIC.....	293
MELODY PERCEPTION AND MEMORY.....	295
MELODY AND RHYTHM.....	297

## INTRODUCTION

The psychological literature on music has expanded rapidly during the last two decades. The sheer mass of published reports forces a highly restricted selection of topics. Moreover, a coherent historical or theoretical context is

difficult to provide for the wealth of accumulated empirical observations. Historically, two main lines of investigation can be identified. One, in the tradition of Helmholtz (1954), emphasizes perception (of musical pitch, in particular); the other, in the tradition of Seashore (1967), emphasizes performance. The present review focuses on research in the first of these traditions, which seeks an explanation, in psychological terms, for such aspects of musical practice as tuning systems, scale structure, harmony, and melody. Research on the perception of timing, meter, and rhythm is not included as it fits more appropriately with studies of music performance.

Most research in the psychology of music occurs within the frameworks of psychoacoustics, Gestalt psychology, individual-differences psychology, and cognitive psychology; but the influences of developmental, cross-cultural, neuroscience, and computational approaches are also evident. The topics reviewed here trace a shift during the last two decades from psychoacoustic to cognitive orientations. More extended and musically realistic materials tend to be employed, and there is a greater emphasis on learning, memory, and attention. Music is compared with other domains of human behavior that require complex internal representations and processes—e.g. vision and language. Psychological studies depend increasingly on music theory, which helps researchers generate testable hypotheses, directs attention to more interesting and subtle musical questions, and provides a context for interpreting empirical results. The review begins with research in the psychoacoustic tradition which investigates the perceptual effects of isolated tones and intervals. Studies concerned with general principles of tonal organization in melody and harmony are reviewed next. The final sections consider perception and memory of extended sequences and the influences of linguistic and music theories on research in music perception and cognition.

## CONSONANCE

Following from the treatise of Helmholtz (1954), the subject of consonance (vs dissonance) has a long tradition of scientific investigation. The multiplicity of methods, results, and theories are not reviewed here (see Malmberg 1918 for an early review). Currently, there appears to be general consensus on two points. First, tonal (or sensory) consonance needs to be distinguished from musical consonance. Tonal consonance refers to the degree to which two simultaneous tones (presented in isolation) sound pleasant, smooth, or blended (Plomp & Levelt 1965). Musical consonance, in contrast, refers to the quality of intervals in a musical context. The latter, while presumed to be related to the former, will also be influenced by the immediate context, the musical style, the musical enculturation of the listener, and other factors (Cazden 1945). With regard to musical enculturation, it should be noted that

most of the studies reviewed in this chapter were done with subjects familiar with traditional Western music. A few studies with non-Western music and non-Western listeners are mentioned.

The distinction between tonal and musical consonance has been useful for sharpening the issues investigated in studies of tonal consonance but has divorced them somewhat from musical considerations. Systematic accounts of musical consonance are largely lacking, with the exception of Terhardt's (1974, 1984; Terhardt et al, 1982a,b; Parnell 1988, 1989) theory of virtual pitch. According to this theory, virtual pitches are heard to the extent that the sounded frequencies match learned harmonic templates. Preliminary results suggest this theory holds some promise to account for such phenomena as the effect of inversion on the consonance of chords, the tone perceived as the root of chords, and the construction of harmonic progressions.

The second point of consensus is that tonal dissonance is best accounted for in terms of beating or roughness. Building on Helmholtz's (1954) basic theory, Plomp & Levelt (1965) proposed a model for computing dissonance. The observation on which their model rests is that the tonal dissonance of an interval formed by simple (sine wave) tones depends on their frequency difference. When the difference is less than a critical bandwidth (the range within which tones interact—in the middle register of the piano, approximately equal to a minor third), the interval is judged dissonant; maximum judged dissonance occurs at about a quarter of a critical bandwidth. Beyond a critical bandwidth, the interval is judged to be consonant. The dissonance of intervals formed by complex (harmonically rich) tones such as those produced by musical instruments is calculated from the dissonance of neighboring harmonics (taking amplitude into account) to give the total dissonance. Calculated values for various types of harmonic tones are presented by Kameoka & Kuriyagawa (1969 a,b), Hutchinson & Knopoff (1978, 1979), and Danner (1985, who also used the values to trace dissonance fluctuations in an atonal composition).

The model predicts that tonal dissonance should be low for intervals with fundamental frequencies (corresponding to the pitches heard) that can be expressed as ratios of small integers, such as the unison (1:1), octave (1:2), perfect fifth (2:3), and perfect fourth (3:4). Somewhat higher dissonance values are predicted for the major sixth (3:5), major third (4:5), minor third (5:6), and minor sixth (5:8). For simple frequency ratios, the lower, more intense harmonics of the two tones either coincide or fall outside the range of interference. For less simple ratios, a greater number of harmonics fall inside the range of interference, causing beating or roughness. Thus, the model is consistent with a large number of perceptual studies showing that judged dissonance increases approximately monotonically with the integers needed to express the fundamental frequency ratios (e.g. Vos & van Vianen 1984). This

is true even though the criteria for judging consonance vary widely in the literature. Van de Geer et al (1962) attempted to sort out the relations among the various criteria, many of which are highly subjective (such as "euphonious" and "beautiful"). Investigators have argued for more objective criteria, such as discriminability between pure and mistuned intervals, sensitivity to beats, identification of the direction of mistuning (Vos 1982), and judgments of whether an interval is heard as one or two tones (DeWitt & Crowder 1987, an operationalization of Stumpf's 1883 doctrine of tonal fusion, which holds that combinations of tones differ in the degree to which they fuse).

## TUNING AND INTONATION

Recent research has focused less on tonal consonance per se than on the implications the concept may have for musical practice and perception. As has long been recognized, tuning systems cannot be constructed such that all intervals are tuned to their theoretical ratios (Helmholtz 1954; Hall 1973, 1974; Burns & Ward 1982; Rasch 1984). For example, in equal-tempered tuning (in which tones are equally spaced in log frequency), minor thirds are flat (by 16 cents) and major thirds are sharp (by 16 cents) compared to their theoretical values in just intonation (there are 100 cents per semitone). Despite this, equal temperament is the standard for tuning fixed-pitch instruments (such as the piano) because it has the practical advantage that the tuning is equally good in any musical key, permitting modulation and transposition. Singers and players of nonfixed-pitch instruments often deviate markedly from the pure ratios in performance (Francès 1958; Rakowski 1990; Shackford 1961, 1962a,b; Sundberg 1982; and other studies summarized in Ward 1970). Intervals [including the octave (Sundberg & Lindqvist 1973; Ohgushi 1983)] tend to be stretched compared to their theoretical values (except for seconds which tend to be compressed). These observations suggest that the simple-ratio theory of consonance has only indirect bearing on musical practice.

A series of recent studies on interval perception, however, shows listeners are quite sensitive to deviations from simple ratios. The threshold for discriminating between pure and mistuned intervals is in the range of 10–30 cents. Vos (1982, 1984; Vos & van Vianen 1984, 1985) examined the effect of various physical parameters such as spectral frequency, tone duration, and fundamental frequency on thresholds for discriminating between pure and tempered (mistuned) intervals. In many cases, the effects could be attributed to the strength of beats produced by the tempered intervals. However, ratings of subjective purity (Vos 1985) deviated from precise predictions of the model (discussed earlier) of Plomp & Levelt (1965) and Kameoka & Kuriyagawa

(1969a,b), suggesting that modifications are needed. Vos & van Vianen (1985), Hall & Hess (1984), and Elliot et al (1987) found tolerance for mistuning decreased when going from less consonant to more consonant intervals, again implicating absence of beating as a cue for pure tuning. The results of the latter two studies also suggested an additional strategy of matching the intervals to abstract standards of interval sizes.

Taking a somewhat different approach, Mathews & Pierce (1980) used tones with stretched harmonics (the distance between harmonics was expanded by a constant multiplicative factor). They found coinciding harmonics produced a sensation of finality or consonance. In a similar vein, Roberts & Mathews (1984) studied how sensitive listeners are to the intonation of chords formed with nonstandard ratios of fundamental frequencies (3:5:7 and 5:7:9). Again, an effect of coinciding harmonics was found in preference judgments, although some listeners favored slightly mistuned versions both of these and of traditional (major and minor) chords. Using novel stimuli (as in these two studies) has the advantage of allowing effects of psychoacoustic properties to be examined while minimizing the influences of experience or learning. Finally, Rasch (1985) and Vos (1988) recently looked at tuning preferences for longer sequences of simultaneous tones. The former found that mistuning of the intervals of the melody was more disturbing than mistuning of simultaneous (harmonic) intervals, supporting the idea that listeners compare melodic intervals to an abstract interval standard. However, Vos showed that the physical purity of simultaneous fifths and thirds accounted for the acceptability of the sequences in his experiment. Taken together, these studies of musical interval tuning support the view that interference between harmonics is the major influence on judgments of tuning, but additional, nonpsychoacoustic factors or strategies also operate.

## CATEGORICAL PITCH PERCEPTION

An apparent paradox arises in the disparity between the accuracy of interval tuning judgments in the studies just reviewed and the deviations from simple-ratio intervals in musical performances. How is it that the sometimes markedly out-of-tune intervals that are performed are not perceived as such? A partial answer to this may be found in studies showing that musically trained subjects perceive intervals categorically. Categorical perception, a phenomenon originally described in the speech literature, is operationally defined (Studdert-Kennedy et al 1970) by: 1. sharp boundaries between category labels assigned to stimuli varying in small steps along a physical continuum, and 2. better discrimination between stimuli in different categories than between stimuli in the same category. (Examples of both criteria are given in the next paragraph.) In the ideal, discrimination performance is no better than the ability to

differentially identify the stimuli (in contrast to the more typical psychophysical result that discrimination is much better than absolute identification).

Burns & Ward (1978) found this pattern in their study of melodic intervals ranging from 250 to 550 cents in steps of 12.5 cents. Musically trained listeners abruptly shifted the labels they assigned to intervals along this continuum [from minor third (three semitones) to major third (four semitones), and then from major third to perfect fourth (five semitones)]. Between the points on the continuum where the shifts occurred, there was virtually 100% consistency about the interval label assigned. For example, one subject (C4) consistently labeled all intervals from 350 to 412.5 cents "major third"; below this range intervals were labeled "minor third," above it "perfect fourth." (When additional response labels for quartertones were added in another condition, they were not used consistently, which suggests that these results were not simply a consequence of restricting the responses to traditional interval names.) The discrimination task required listeners to judge which of two intervals was wider, and the data were very close to the predictions from the identification scores. That is, intervals were discriminated only to the extent they were labeled differently, producing peaks at the category boundaries. For example, this same subject was close to chance discriminating between intervals in the range labeled "major third," but was above 75% correct at the ends of the range. Burns & Ward (1978) found no such peaks for musically untrained listeners.

This is perhaps the clearest reported case of categorical perception found for musical intervals, but similar results appear in other studies. Siegel & Siegel (1977a,b) found the following results for musicians with relative pitch (the ability to name tones when a reference pitch is present): 1. sharp identification boundaries; 2. discrete steps in magnitude estimates corresponding to interval category boundaries; 3. no effect on magnitude estimates of changing the range of the stimulus set (i.e. no adaptation effect; Helson 1964); and 4. an inability to distinguish "sharp" and "flat" intervals within categories. Subjects with absolute pitch (the ability to name tones in the absence of a reference pitch) showed the first and third effects when presented with single tones in isolation. Zatorre & Halpern (1979) again found sharp identification boundaries, but here discrimination performance exceeded predictions from the identification responses. The latter result suggests listeners could use acoustic information in addition to the category labels to make the discrimination. The fact that this study, unlike the others, used simultaneous (harmonic) intervals probably contributed to the result; successive (melodic) intervals may be coded more categorically because they require retaining the pitch relations over time. This study also found that the category boundaries could be shifted by preceding the test trials with an adaptor (120 presentations

of an interval at one end of the stimulus continuum), a result analogous to adaptation found for speech sounds. Finally, Wapnick et al (1982) investigated whether labeling (of interval category and intonation quality) and discrimination would be more accurate when intervals were presented at the end of a tonal melody. Although performance was better for intervals in context than for isolated intervals, musicians still tended to produce the categorical pattern of results.

The categorical perception of musical intervals suggests that at some level of processing, pitch information is coded with respect to discrete pitch categories corresponding to the intervals in the musical scale. If this is the case, categorical perception should be limited to trained musicians, and indeed large differences as a function of musical training are found in all the studies cited (as well as in Crowder's 1985 study of major and minor triads). Nonmusicians exhibit neither sharp categorical boundaries nor peaks in discrimination functions. That pitch is coded in terms of learned musical categories is further supported by Francès's (1988) finding that listeners notice mistunings of tones less when they conform to the melodic and harmonic tendencies of the tones in the context than when they do not. These findings should not be taken to say, however, that intervals cannot be coded precisely by musicians. The tuning judgments summarized in the last section indicate that, under some circumstances, they can be. Tuning experiments typically use harmonically rich tones and simultaneous (harmonic) intervals, and subjects are often given feedback about whether or not their responses are correct. In contrast, studies showing categorical results typically use sinusoidal tones and successive (melodic) intervals, and no feedback is given. These methodological differences may account in large measure for the different estimates of intonation sensitivity, although no systematic study of these factors has been reported.

## ABSOLUTE PITCH PERCEPTION

Absolute pitch refers to the ability to name an isolated musical tone (presented without an objective reference tone) or, conversely, to produce a tone identified by name only. Although the practical significance of this ability for musicians is limited, it has received considerable attention owing to its apparent rarity in the population. Ward & Burns (1982) provide a review of most of the literature on this topic, and a few more recent studies are summarized here. Miyazaki (1988) had listeners assign names to electronically generated sine wave tones (eliminating possible timbral cues of musical instruments such as piano; see Lockhead & Byrd 1981). As in other studies, listeners with absolute pitch showed: 1. high accuracy and short latency of naming; 2. a predominance of octave errors when errors occurred; and 3. a

categorical pattern of classifying tones (which differed in steps of 20 cents). The responses of listeners without absolute pitch were slower, more variable, and showed neither a tendency toward octave errors nor sharp categorical boundaries; they apparently relied primarily on an impression of overall pitch height. What is unusual in this study is the prevalence of absolute pitch. In the first experiment, 7 of 10 listeners (university music students) showed absolute pitch. Of the 39 music students in the second study, 12 performed at a rate of 86.7% or better in responding within one semitone. Essentially all of these subjects began musical training at the age of 3–5 years, suggesting that early exposure underlies the ability. Curiously, these subjects did not recognize all 12 tones of the chromatic scale equally well, but were better on the white notes of the piano (and especially the tonally important notes of C major). Although the possibility of a response bias cannot be eliminated, the authors suggest this finding may be related to the fact that early piano and ear training lessons tend to begin with the C major key.

In a somewhat similar vein, Terhardt & Ward (1982) and Terhardt & Seewan (1983) showed a fairly widespread ability to judge whether or not a piece was played in the notated key (indicated to listeners by a simplified score). These studies used as stimuli the initial segments (approximately 5 sec) of Bach's preludes from the *Well-Tempered Clavier*, which were played either in the notated key or transposed up or down by an interval ranging from 1 to 6 semitones. Accuracy rates were surprisingly high. For example, Terhardt & Seewan (1983) found 45% of the listeners (only some of whom claimed absolute pitch) were reliably able to distinguish between the notated key and a transposition by one semitone. The results were similar whether piano or electronic timbres were used. These performance rates exceed what would be predicted based on pitch-naming studies for listeners without absolute pitch, although the specific comparison was not made. Their subjects were not tested on isolated tones, so it is unclear whether they had better pitch-identification abilities than expected or whether identifying keys is a different process from identifying isolated pitches. Both abilities show a bimodal distribution in the population, suggesting they may be related.

Finally, Zatorre & Beckett (1989) recently examined a different question—namely, the nature of the mental code used by musicians with absolute pitch. Such subjects were required to name three successive piano tones after a delay of up to 27 sec. During the retention interval, they performed a verbal interference task (counting backwards by threes) or a musical interference task (humming or singing a chromatic scale). Neither task affected the accuracy of reporting the tones (in contrast to many studies showing interference effects on both musical and verbal memory), suggesting that the mental code is neither exclusively verbal nor exclusively acoustic in nature. Rather, multiple codes appear to be employed, including these and possibly

also kinesthetic codes (e.g. specifying the finger position for producing the tone on an instrument).

## MODELS OF TONAL RELATIONS

In general, pitch is coded primarily in terms of the intervals between simultaneous and successive pitches. For example, a melody is heard as the same melody even though it begins on a different pitch (is transposed) as long as the intervals between tones are unchanged. Moreover, whereas absolute pitch ability is relatively rare, most musicians have quite accurate relative pitch ability. How is interval information perceived and remembered? In physical terms, tones vary along the continuous dimension of frequency measured in Hertz (cycles per second). The corresponding perceptual attribute—pitch—is a logarithmic function of physical frequency over most of the musical range, and the perceived sizes of musical intervals depend on distances along this logarithmic scale. Additional evidence for the logarithmic scale comes from musical practice. The tones used in music consist of a discrete set of values along this continuum. The chromatic scale of Western music, for example, has 12 semitones per octave that are (in equal-tempered tuning) equally spaced in log frequency. The same pattern repeats in every octave; corresponding tones in the different octaves are given the same name (e.g. C, C#, etc) and are said to be octave-equivalent.

Factors other than distance along this single dimension of pitch also influence the degree to which two tones are perceived as related. Various proposals have been made for summarizing these factors, often in the form of geometric models (reviewed by Shepard 1982). These models variously emphasize different factors: pitch height (the unidimensional scale just described); the chroma circle (on which tones separated by semitones are adjacent and octave-related tones are considered equivalent); the circle of fifths (on which tones separated by perfect fifths, or seven semitones, are adjacent and octave-related tones are considered equivalent); and the sub-cycles generated by major thirds (four semitones) and minor thirds (three semitones).

Models jointly emphasizing pitch height and the chroma circle (producing a helix or variants of it) have been proposed frequently (e.g. Bachem 1950; Shepard 1964; Pikler 1966; and sources cited in these papers). Shepard (1964, 1983 with accompanying sound examples) argued that the sense of chroma (pitch class) is psychologically separate from the sense of overall pitch height. His study employed tones produced according to the following method (variants of which have been employed in numerous subsequent experiments). Each tone consisted of ten sinusoidal components at octave intervals. For example, one tone might consist of Cs sounded in ten octaves, while another

of C#s sounded in ten octaves. The amplitudes of the components were determined by a sinusoidal function increasing from threshold at the low end of the frequency range to a maximum in the center of the range, and then decreasing to threshold at the high end of the range. Sounding these tones in succession produces the perception of moving from C to C# but not (owing to the amplitude envelope) of changing pitch height. After continuing the process for a total of 12 steps (with components moving along the chromatic scale), a tone physically identical to the first tone is reached (components are filled in at the bottom of the pitch range as components drop out at the top).

Listeners in Shepard's study (1964) judged two tones as ascending if the distance between components is shorter in the direction of increasing frequency (e.g., a tone with C components followed by a tone with E components) and as descending if the distance is shorter in the direction of decreasing frequency (e.g. a tone with C components followed by a tone with A components). Tones with equal distances in the two directions (e.g. a tone with C components followed by a tone with F# components) were perceived as either ascending or descending (with stable individual differences in the direction of motion, according to Deutsch 1986b, 1987; Deutsch et al 1986; Deutsch et al 1987). From this, Shepard argued for a circular dimension of pitch chroma (with octave-related tones equivalent) that is independent of pitch height. Burns (1981), however, showed the same effects with tones whose components were not separated by octaves, weakening the argument that a circular dimension of chroma (identifying octave-related tones) is implicated. Moreover, Nakajima et al (1988) recently demonstrated a second circular dimension (corresponding to a one-third-octave periodicity) when the components form major triads. Going even further in this direction, Allik et al (1989) provided a general model predicting perceived pitch motion with randomly selected components. For present purposes, it is important to note only that ample evidence from other perceptual studies (and musical practice) supports the notion that tones at octave intervals are in some sense equivalent or at least highly related. In addition, support for the helical model (combining pitch height and the chroma circle) has been obtained recently in a scaling study by Ueda & Ohgushi (1987) in which listeners judged the similarity of pairs of tones generated according to Shepard's (1964) general method.

Other models emphasize different factors that may govern the degree to which tones are heard as related. The dimensions of Lakner's (1960) and Shepard's (1982, "melodic map") models are the chroma circle and the circle of fifths. The models put forth by Longuet-Higgins (1962a,b), Hall (1973, 1974), Balzano (1980), and Shepard (1982, "harmonic map"), which can be traced back to Helmholtz and Euler, are generated by major thirds and perfect fifths. Although these models are intuitively appealing because certain musi-

cal structures, such as scales and triadic harmonies, seem to “fall out” of them, direct supporting evidence from perceptual studies is lacking.

Moreover, Krumhansl (1979, 1990a) argued that geometric models of pitch relations are, in general, limited in two important ways when the pitches are heard in context. First, the geometric models just described all assume that intervals of equal size are perceived as equal. This may be true for isolated intervals, but it is not true for intervals in tonal contexts. The tones C and G, for example, were judged by listeners to be more similar or related in the context of a C major key (in which they play the structurally important roles referred to as tonic and dominant, respectively: see next section) than were the tones C# and G#, even though both intervals are perfect fifths. The second limitation is that spatial models cannot depict temporal-order effects because spatial distances are necessarily symmetric. For example, in a C major key context, B followed by C received a higher rating of similarity or relatedness than C followed by B (the B, as a leading tone, tends to be followed by C, the tonic). The appeal of geometric models, however, is that they summarize complex pitch relationships in a form that can easily be understood.

## TONAL HIERARCHIES

Krumhansl & Shepard (1979) devised the probe-tone technique to investigate one aspect of how a tonal context influences the perception of musical pitch. Music theorists (e.g. Meyer 1956; Lerdahl 1988) describe a hierarchy of tonal functions, with some tones more stable, structurally significant, or final-sounding than others. In rough categorical terms, the tonic, which heads the hierarchy, is followed by the fifth (dominant) and third (mediant) scale degrees, which are followed by the remaining scale degrees, and finally the nonscale (nondiatonic) tones. In Western music, the seven-tone major and minor diatonic scales are the most frequently used; see Krumhansl (1990a) for a description of their construction. The probe-tone technique, as originally applied, operationalized the notion of a tonal hierarchy as follows. An incomplete C major scale (without the final tonic, C) was sounded in either ascending or descending form. This context, intended to establish the key of C major, was followed on successive trials by each of the chromatic scale pitches in the next octave (the probe tones). Listeners rated how well each tone completed the scale. The ratings of listeners with musical training (instrumental or vocal instruction) conformed to the qualitative predictions of music theory, whereas the ratings of listeners without musical training were dominated by another factor, namely the distance between the probe tone and the last tone of the context.

Krumhansl & Kessler (1982), using different key-defining contexts (tonic

triads and chord cadences for both major and minor keys), again recovered the predicted tonal hierarchy in ratings of how well the probe tones “fit with” the contexts. The ratings given the probe tones in major and minor key contexts were then used to obtain a spatial representation of the perceived distances between musical keys. The analysis, which took the following steps, was based on the assumption that closely related keys have similar tonal hierarchies. First, rating profiles for the major and minor keys were shifted to different tonics to produce profiles for all 12 major and 12 minor keys; this was justified by the equivalence of the tonal hierarchies under transposition. Second, all pairs of profiles were correlated to obtain an indirect measure of how closely related each key is to each of the others; keys were considered closely related to the extent that their tonal hierarchies were similar as measured by the correlations. Third, the correlations were analyzed using multidimensional scaling, which produces a spatial representation of points such that interpoint distance is, as much as possible, inversely related to the similarity measures (in this case the correlations of key profiles). The multidimensional scaling solution located the points for the 24 major and minor keys on the surface of a torus in four dimensions. In conformance with musical intuitions (and theoretical predictions—e.g. Schoenberg 1969), the perceived distances between keys were related to two factors: the circle of fifths and the relative and parallel major-minor relations. For example, the C major key had as its neighbors G major (one step “up” the circle of fifths), F major (one step “down” the circle of fifths), A minor (the relative minor), and C minor (the parallel minor). Thus, the information contained in the tonal hierarchy is sufficient to generate a concise and musically interpretable representation of key distance.

One motivation for obtaining the probe-tone ratings with contexts that unambiguously define keys (Krumhansl & Kessler 1982) was to provide standard profiles to compare with probe-tone ratings made with contexts that are less clear tonally. This has been done in a number of cases. Krumhansl & Kessler (1982) used the standard profiles to trace (on the map of musical keys just described) how the sense of key develops and changes over time. Trained musicians rated probe tones presented after each successive chord in nine-chord sequences, some of which contained modulations (changes) between keys. The sense of key was found to develop rapidly, even before the tonic triad was sounded. Shifts to keys that are theoretically closely related were assimilated more readily than shifts to distantly related keys. Thompson (1986), in a similar application to Bach chorales, detected an asymmetry in modulation distance: The initial key continued to have a stronger influence after modulations toward the dominant side of the circle of fifths (“up”) than toward the subdominant (“down”). Directional asymmetries also appeared in identification of key changes and judged modulation distance (Thompson &

Cuddy 1989). Krumhansl & Schmuckler (1986) used the standard profiles (Krumhansl & Kessler 1982) to investigate whether listeners can perceive two keys simultaneously using a bitonal passage with materials from two distantly related keys. The tonal hierarchies of the two keys were both evident, but various experimental tasks showed listeners were unable to attend selectively to either one of the two keys. In another study, Krumhansl et al (1987) used contexts drawn from 20th-century atonal (serial) compositions. Listeners with less music training tended to produce probe-tone ratings similar to those of keys (weakly) suggested by the contexts. In contrast, listeners with more such training (particularly academic) tended to produce ratings similar to the tonal hierarchy of a distant key, suggesting they tended to reverse the normal tonal interpretations.

Two studies have adapted the probe-tone technique to non-Western music: Castellano et al (1984) to North Indian music, and Kessler et al (1984) to Balinese music. Both studies found the probe-tone ratings reflected style-appropriate tonal hierarchies, even some produced by listeners unfamiliar with the style. This result may depend on the fact that the contexts preceding the probe tones were relatively complex and explicitly emphasized the structurally important tones. These tones tended to be sounded more frequently, with longer durations, and at prominent positions within the phrases. Thus, these factors may enable listeners to identify the focal tones in novel musical styles. This possibility is supported by an extensive series of experiments conducted by Oram (1989), who investigated whether frequency of occurrence was sufficient to induce a tonal hierarchy as measured in the probe-tone task. In the context sequences, one tone occurred eight times, two others four times, and four others once each. In some cases the tones constituted a diatonic set (the tones of the normal major scale), and in other cases they did not (conforming to no major or minor scale), but in all cases the probe-tone ratings were strongly influenced by the frequency with which the tones appeared in the context. Thus, tone distributions provide a means through which a tonal hierarchy might become established in an unfamiliar style.

Most experiments, however, have focused on pitch structures in Western tonal-harmonic music rather than in earlier or later Western styles or non-Western music. The tonal hierarchies of major and minor keys (as described by music theorists and measured by the probe-tone ratings) influence the degree to which two tones are perceived as related (Krumhansl 1979, 1990a), reaction times in judging key membership (Janata & Reisberg 1988), judgments of phrase endings (Palmer & Krumhansl 1987a,b; Boltz 1989a,b, which also showed influences of rhythmic structure), expectations for melodic continuations (Schmuckler 1989), and patterns of memory confusions (Krumhansl 1979). Moreover, these psychological measures correlate strongly with the distributions of tones in stylistically familiar musical compositions

(Krumhansl 1990a,b), reinforcing the idea that the tonal hierarchies are learned through sensitivity to tone distributions within a stylistic tradition.

## HARMONY AND KEY

The first part of this section takes up experimental studies that show effects for chords that are analogous to many of those just described for tones. In the latter part of the section we consider how a key becomes established initially. A tonal context establishes a hierarchy of structural significance, with the I (tonic), V (dominant), and IV (subdominant) heading the hierarchy (Krumhansl et al 1982b; Krumhansl 1990a). These harmonic hierarchies generate the same map of key distance as that generated by the tonal hierarchies (described above) and correlate with the frequency with which chords appear in musical compositions (Krumhansl 1990a). The harmonic hierarchies can also be predicted from the positions of the chord components in tonal hierarchies (Krumhansl & Kessler 1982), suggesting strong interdependencies between the two types of elements: tones and chords. The harmonic functions of chords in keys also affect the degree to which chords are heard as related (Krumhansl et al 1982b; Bharucha & Krumhansl 1983; Krumhansl et al 1982a; Roberts & Shaw 1984) and the probability they are confused in recognition memory (Bharucha & Krumhansl 1983; Krumhansl et al 1982a; Krumhansl & Castellano 1983). Perceived chord relations, in turn, determine harmonic expectancies (Bharucha & Stoeckig 1986, 1987; Schmuckler 1989) and mirror the frequency of chord progressions in music (Krumhansl 1990a). Finally, changing the tonal context produces regular effects on both memory confusions and relatedness judgments (Bharucha & Krumhansl 1983; Krumhansl et al 1982a), indicating strong ties between harmony and key. Bharucha (1987; Bharucha & Olney 1989) has recently developed a connectionist model that accounts for many of these results. Tone units are activated by the events in a musical sequence. Activation then spreads to chord and key units, and continues to reverberate bidirectionally until the network settles into a state of equilibrium. Computer simulations produce many of the same patterns of expectations, relatedness judgments, and memory errors as listeners in the experiments just reviewed.

Thus experiments show numerous parallels between tones and chords in how they are perceived in musical contexts (summarized in Krumhansl 1990a). For both, there is a well-defined hierarchy of structural significance, with harmonic hierarchies dependent on tonal hierarchies. Both mirror the distribution of elements in music, suggesting they are established in the music by repetition and other forms of emphasis, and generate the same measure of interkey distance. Perceived relations between tones and between chords are strengthened for elements that are structurally significant within the tonal context. Moreover, a less-stable element is perceived as more related to a

stable element following it than is a more stable element to a less stable element following it. [The tendency to hear the second of two neighboring tones as structurally more stable was codified by Bharucha (1984a) as the melodic anchoring principle.] Analogous results are found in recognition-memory measures and in the fact that listeners remember structurally significant elements better overall. Such studies are concerned with how these musical elements (tones and chords) generally function within the style—that is, in an abstract or normative sense, once the tonality or key has been established.

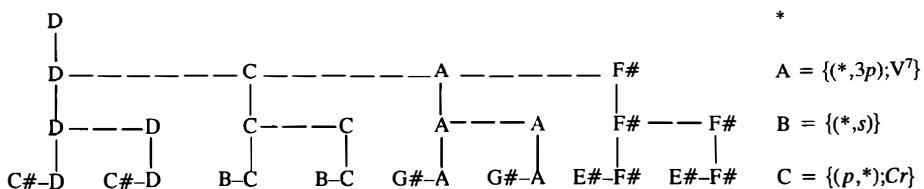
The problem of how a key becomes established initially has received less attention. Cohen (1977) found music students were quite accurate in producing the tonic of the key of short excerpts from the *Well-Tempered Clavier* (for example, they were 75% correct after hearing just the first four musical events). Butler & Brown (1984) report that three-tone sequences yielded correct judgments of possible tonics 83–91% of the time when the three tones included the tritone formed by the fourth and seventh scale degrees, and 96–98% of the time when the tones were any three other diatonic scale degrees. Their emphasis on the tritone stems from the fact that it (together with any third diatonic tone) uniquely specifies a major key, but their data (even corrected for guessing) do not support the idea that this tritone increases accuracy in judging the tonic (Krumhansl 1990b). Listeners, however, do seem to be aware of the multiple tonics possible when this tritone is absent. Cross et al (1985) found that other three-tone combinations provided clearer tonal cues (especially the first, second, and fourth scale degrees). Brown (1988) demonstrated that the order in which tones appear can have a large effect on key judgments; different tonics were chosen when the same tones were reordered, although general principles for predicting the judgment of tonic remain to be articulated. Finally, two other approaches to understanding the key-finding process take the form of computer algorithms. Longuet-Higgins & Steedman's (1971) algorithm eliminates keys on the basis of whether or not the tones in the musical sample are contained in the diatonic major and minor scales. Krumhansl & Schmuckler's algorithm (described in Krumhansl 1990a) matches (by correlation) the distribution of the tones in the musical sample to the tonal hierarchies of major and minor scales. The second algorithm was found to be more efficient (Krumhansl 1990a), but other factors (particularly temporal order and harmonic implications) may also help listeners ascertain the key quickly so that the tonal and harmonic functions of the sounded events can be appreciated.

## CODING MODELS OF MUSIC

The experiments just reviewed describe the perceived relations among the elements of traditional Western music (tones, chords, keys) in an abstract or

general sense. They are not concerned with how the elements are employed in simultaneous and successive combinations in specific passages of music. [See Bharucha (1984b) for a discussion of the distinction between tonal hierarchies and event hierarchies as an example of the contrast between stylistic norms and characteristics of particular pieces.] Intuitively, the construction of melodic and harmonic sequences seems to be rule governed. Various suggestions have been made about how to formalize these rules. In an important paper, Simon & Sumner (1968) articulated a number of basic premises that have influenced subsequent theory. First, the psychological purpose of such rules is to enable listeners to develop expectations for successive events ("pattern induction"; see also Meyer 1956). Second, the rules operate on small and well-defined sets of elements ("alphabets" such as chromatic scales, diatonic scales, and triads). Third, the rules can be described using a small number of operators (such as "same" and "next") on the specified alphabet. Fourth, the rules can be applied recursively, producing hierarchically organized patterns of subpatterns. And finally, musical patterns are multi-dimensional: Patterns exist simultaneously on a number of different levels (metric, rhythmic, melodic, harmonic).

Deutsch & Feroe (1981) proposed a model for representing pitch sequences in tonal music; it follows the general form outlined by Simon & Sumner (1968). The model is perhaps best described with respect to a particular example:



The lowest level shows the actual notes of the passage (from Beethoven, Sonata op. 22). The reference pitch for the whole passage (denoted \* at the highest level) is D, the fifth scale tone of the key of the passage, which is G minor. The level below this is represented by the formalism A = {(\*, 3p); V<sup>7</sup>}, where the operator p ("predecessor") is applied three times to the alphabet V<sup>7</sup> (the dominant seventh, D F# A C D). In this alphabet, the predecessor of D is C; the predecessor of C is A; and the predecessor of A is F#. This gives the tones D, C, A, and F# shown at the second level from the top of the hierarchy. The next level down is represented by B = {(\*, s)}, where the operator s ("same") means simply that each note is repeated. Finally, the lowest level is represented by C = {(p, \*); Cr}, which means that each note is preceded by its neighbor on the chromatic scale (denoted Cr). This example

illustrates a number of basic principles of the model: hierarchical organization, a small set of alphabets and operators, and different alphabets and operators at different hierarchical levels.

In an empirical test, Deutsch (1980) showed that tonal sequences with this kind of hierarchical, rule-governed organization were more accurately recalled than unstructured sequences in a musical dictation task. Moreover, inappropriate temporal segmentation of the rule-governed sequences (breaking up the subgroups) significantly hurt recall. However, Boltz et al (1985) found only weak effects of rule-based patterning; sequences generated by recursive application of rules were better remembered only at certain rates of presentation. Moreover, Boltz & Jones (1986) found that rules at higher hierarchical levels did not consistently aid reproduction of tone sequences. Instead, other factors predominated, such as the number and timing of contour changes (changes from ascending to descending lines or vice versa) and the relative position of melodic and temporal accents. Thus, the rules as formulated have inconsistent effects and interact with other factors, suggesting that further tests are needed to clarify the nature of tonal patterning. Attention might also be directed toward the question of how well such rules characterize actual musical compositions, and whether the sets of rules and/or alphabets might be expanded or modified to allow more flexibility. An additional question is how theoretical descriptions of melody, harmony, rhythm, and meter might be combined, or at least coordinated, to reveal their interdependencies.

## LINGUISTIC THEORY APPLIED TO MUSIC

Other suggestions for formally representing musical structure come from analogies to language. Certain structural principles of natural language grammars have been applied to music. Lindblom & Sundberg (1970) argued for a new kind of theory of music that accounts for musical behaviors (composition, performance, perception) the way Chomsky's approach (1968) treats language: ". . . the research problem can in our opinion be formulated in the following fashion: Given a certain well-defined class of melodies what are the principles and laws by means of which the metric, harmonic, and tonal facts of these melodies can be derived?" In an initial contribution along these lines, Lindblom & Sundberg applied rules of linguistic prosody to a set of Swedish nursery tunes, noting that the procedures for deriving a stress or prominence contour from a tree diagram are very similar in the two cases. The system of prominence rules provides a framework for analyzing formally metric, harmonic, and tonal materials; it was used to generate novel but stylistically similar melodies. Variations of a lullaby folk melody were produced by a similar grammar (Sundberg & Lindblom 1976). Other contributions drawing

on an analogy between music and language include: a grammar for setting words to music in Gregorian chant (Chen 1983), a grammar for generating jazz chord sequences (Steedman 1984), and computational models for assigning rhythmic and tonal descriptions to performed music (Longuet-Higgins & Steedman 1971; Longuet-Higgins & Lee 1982; Longuet-Higgins & Lisle 1989). Narmour (1989) has recently proposed a theory of melody based on a few elementary principles of similarity, proximity, good continuation, and reversals. These principles produce a small number of archetypal realizations and can be applied recursively to generate multiple hierarchical levels in networks of simultaneous structures.

Currently, the most extensive and influential theory applying linguistic concepts to music is that of Lerdahl & Jackendoff (1983). Their model contains four kinds of structural representations: grouping (which partitions the music into hierarchically organized temporal segments), meter (which assigns periodic patterns of stress), the time-span reduction (which assigns a tree structure specifying the relative dominance of each surface event), and the prolongation reduction (which provides a description, in the form of a tree, of patterns of harmonic tension and relaxation). Parts of this extensive theory have been tested in experimental studies. Deliège (1987) found general support for the grouping principles in judgments of segment boundaries in short musical excerpts. According to the theory, grouping is based on both temporal characteristics (such as slurs, rests, and prolonged sounds) and changes of musical parameters (such as register, dynamics, timbre, and articulation). Clarke & Krumhansl (1990) found that these same kinds of principles operate on a global level, defining major sections within extended pieces. Palmer & Krumhansl (1987a,b) investigated the perception of phrase structure by presenting segments ending at different points in the music. The listeners judged how good or complete a phrase the sounded segment formed, and their responses conformed to two components of the theory: the time-span reduction and the metrical hierarchy (which has since been shown to influence judgments of metrical stability and memory confusions between temporal positions, Palmer & Krumhansl 1990). Finally, Bigand (1990) found evidence that listeners abstract the underlying harmonic structure that is represented by the prolongation reduction. This and other formal theories promise to stimulate a great deal of research in the future about the nature of musical pattern perception. Although currently limited in various ways, these theories provide a framework for understanding music in psychological terms, simultaneously elucidating the music itself and the perceptual and cognitive processes through which it is understood and appreciated. Discussion of some of the promises and problems in this approach can be found in commentaries by West et al (1985), Rosner (1988), and Clarke (1989).

## MELODY PERCEPTION AND MEMORY

Theories of melody perception and memory assume that listeners group individual tones into longer temporal units. Principles of a Gestalt nature influence the formation of these units, as has been documented by extensive empirical research (see Bregman 1990; Deutsch 1986a, for reviews). Much of this research uses the methodology of stream segregation, which refers to the perceptual organization of a sequence of (usually rapidly presented) tones into separate acoustic events or "streams." Factors or attributes known to influence whether elements divide into multiple streams include: frequency separation (pitch differences), presence or absence of frequency transitions (glides) between tones, the complexity of the contour (pattern of ups and downs), temporal proximity, rate of presentation, onset and offset asynchrony, timbre differences, spatial location, intensity differences, number of repetitions, attentional instructions, and prior knowledge of the component patterns. It is impossible to review this vast literature here, but two general points should be noted. First, Bregman (1990) argues that the empirical effects reflect fundamental principles that organize the complex acoustic environment into coherent events; sounds from a single source will tend to be continuous; similar in pitch, intensity, and timbre; close in spatial location; and so on. Second, Gestalt principles have influenced various theoretical descriptions of music (e.g. Meyer 1956; Lerdahl & Jackendoff 1983; Narmour 1989), although their applicability to complex and musically representative materials has not been studied systematically. [An important exception is Huron's (1989a,b; Huron & Fantini 1989) analysis of polyphonic music, which relates compositional techniques to the research on stream segregation.]

Specifically musical factors, such as scale structure, harmony, and key also influence the way sequences are encoded and remembered. Results of this kind suggest that listeners interpret the sounded tones by using their knowledge of the interval patterns typical of the style to apprehend and retain larger and more musically meaningful patterns. In an influential early paper along these lines, Dowling (1978) demonstrated the importance of diatonic scale structure in recognition memory for transposed sequences. In the experiment, a target sequence was presented first, followed by two comparison sequences; the listeners were required to say which of the two comparison sequences was the same as the target sequence. One of the comparison sequences was an exact transposition (changing the key, but maintaining the size of the intervals and the contour); the other was a transposition up or down the scale of the target melody (maintaining the key and contour, but altering the size of the intervals). Neither musicians nor nonmusicians could reliably identify the matching melody. Changes of contour were, however, much easier to reject.

for both groups. From this, Dowling concluded that musical scales provide a basic framework on which the melodic contour is hung.

In an extensive series of studies, Cuddy and collaborators (Cuddy & Cohen 1976; Dewar et al 1977; Cuddy et al 1979; Cuddy et al 1981; Cuddy & Lyons 1981) employed a similar measure of recognition accuracy for transposed sequences. These studies expand the set of musical factors known to influence memory to include: triadic structure, repetition of the tonic, leading tone to tonic ending, harmonic cadence (V–I), modulation within the sequence, and key-distance of transposition (tritone vs dominant). Bartlett & Dowling (1980) also found a key-distance effect such that near-key lures (inexact transpositions) were harder to reject than far-key lures. Studies by Dowling & Bartlett (1981) and DeWitt & Crowder (1986) showed that the relative importance of pitch position within the tonal scale (compared to contour information) increased from short-term to long-term memory [although Dowling (1986) was able to alter the effect by instructions]. These results suggest that knowledge of tonal structure becomes even more important for retaining melodic patterns over longer durations. In a similar spirit, Edworthy (1985) concluded that whereas contour is coded more precisely for shorter sequences and for earlier serial positions in longer sequences, interval information dominates at later serial positions in longer sequences. Finally, Watkins (1985) found a memory advantage for more clearly diatonic sequences. This advantage disappeared, however, when the interval sizes were reduced by a constant (logarithmic) factor; for the resulting sequences, which have abnormal intervals, contour alone influenced recognition performance.

Most of the experiments just reviewed use transposition of short sequences specially constructed to isolate the musical factor(s) of interest. A few studies have used more complex transformations and/or stimulus materials drawn from musical compositions. Recognition of mirror forms [inversion (inverting pitch), retrograde (inverting time), and retrograde inversion (inverting both pitch and time) as employed in 12-tone serial music] has been the focus of a number of experiments (e.g. Francès 1988; Dowling 1972; Krumhansl et al 1987); these find some evidence for perceived melodic invariance under these transformations. Pollard-Gott (1983) used excerpts presenting the two themes from Liszt's Sonata in B minor and their variations. With repeated listenings, the excerpts based on one theme came to be distinguished from the excerpts based on the other theme, as measured in both similarity and classification judgments. Rosner & Meyer's (1982) listeners learned to classify musical excerpts according to their underlying melodic "archetypes" (which describe the process through which a melody moves toward its point of closure; Meyer 1973). Welker (1982) and Carterette et al (1986) demonstrated that listeners abstract the prototypical melody from transformed versions of it. As transformations, the former used inversion, syncopation, reduction of interval

size, temporal elaboration, and deletion of a measure from the prototype; the latter used octave displacements (changing contour), altered intervals (preserving contour), changed loudness, and changed note duration. Both studies found regular effects of transformation distance. Finally, Serafine et al's (1989) listeners judged that excerpts with the same hierarchic analysis (Schenker 1979) were similar despite radical harmonic differences on the surface. The perception and memory of musical sequences are thus governed by many different factors, some highly complex and subtle. Future research extending this line of investigation might increasingly draw on music-theoretical concepts of melodic structure.

## MELODY AND RHYTHM

The relationship between tonal and rhythmic aspects of music, a centrally important topic, has received relatively little attention. Both theoretically and empirically, these two aspects tend to be treated separately. Clearly, both aspects influence music perception and memory, but it is unclear whether they are truly interactive or simply have additive effects. A number of studies show that rhythmic structure influences judgments of pitch information. Jones et al (1981) found that a target (pitch) interval that is rhythmically differentiated from its context is more accurately perceived (as measured by temporal order judgments) than one that is not. Jones et al (1982) manipulated accent structure and obtained effects on pitch recognition. They proposed that listeners dynamically allocate attentional resources over time (with greater attention at some moments than at others), a theoretical notion elaborated by Jones (1987). Dowling et al's (1987) study required detecting a melody interleaved with distractor tones. The findings indicated attention is directed not only to certain moments in time but also to certain ranges in pitch. The study of dynamic attention allocation over time appears to be a promising approach to expanding theories about attention.

A number of studies examine the combined effects of tonal and rhythmic patterns. In a scaling study of rhythmically varied melodies, Monahan & Carterette (1985) identified three rhythmic and two tonal dimensions underlying judgments of melodic similarity; intersubject trade-offs between the weights for the two kinds of dimensions suggest some measure of independence. Palmer & Krumhansl (1987a,b) found pitch and temporal components made independent and additive contributions to judged phrase structure. However, other results suggest interactions between temporal and pitch patterns. When the patterns are out of phase, recall is impaired (Deutsch 1980; Boltz & Jones 1986; Monahan et al 1987), although this effect is not found consistently (Smith & Cuddy 1989). In addition, Jones et al (1987) found poorer recognition of melodies presented in a rhythm different from the

original rhythm, suggesting that these aspects are encoded together in memory. These findings are not necessarily contradictory. Judgments of higher-order properties (memory and similarity of melodies, and judgments of phrase structure) would be expected to show joint influences of the tonal and rhythmic components. To say that they are independent (noninteractive) is simply to say that the effects do not require supposing that additional factors emerge when both tonal and rhythmic components are varied. If the two components are varied in a way that is mutually incompatible or inconsistent, then they may well interfere with one another.

The perception, memory, and production of temporal patterns independent of pitch patterns have been studied extensively. This literature, however, is more closely related to that on musical performance, which is beyond the scope of this review. However, research on the temporal dimension of music has developed along lines parallel to that on musical pitch. Studies of isolated temporal intervals have led to studies of more complex and musically realistic temporal patterns. The results are interpreted in terms of such concepts as grouping, hierarchical organization, rhythm, and meter. Formal models have been proposed and tested, and these draw on concepts from music theory. Finally, structural and interpretative aspects are found to influence expressive timing in musical performances in ways that can be modeled precisely.

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