Music Perception and Cognition

Timothy C. Justus
University of California, Berkeley

Jamshed J. Bharucha
Dartmouth College

Music perception and cognition is the area of cognitive psychology devoted to determining the mental mechanisms underlying our appreciation of music, and in this chapter we review the major findings. We begin with the perception and cognition of pitch, which is the most thoroughly researched area in the field. We then consider perceptual organization in music in the dimension of time, followed by research in musical performance. Next, we review the literature concerning the cognitive neuroscience of music. Finally, we conclude with a discussion of musical universals and origins.

The size of the literature in this field prevents an exhaustive review in the course of a single chapter. The reader is referred to specific reviews in each section, including various chapters appearing in the edited volumes of Deutsch (1982, 1999b), McAdams and Bigand (1993), and Deliège and Sloboda (1997). Additional broad reviews include those by Dowling and Harwood (1986), Krumhansl (1991, 2000a), and Sloboda (1985). For psychologically informed discussions of issues in musical aesthetics, a topic that will not be discussed here, works by Meyer (1956, 1967, 1973, 2000) and Raffman (1993) are recommended.

Pitch

The Constructive Nature of Pitch Perception

Pitch perception is an excellent example of the pattern recognition mechanisms used by the auditory system to parse the simultaneous and successive sounds that make up the auditory scene into distinct objects and streams (Bregman, 1990; McAdams & Drake, this volume). When listening to music or speech in a naturalistic setting, several instruments or voices may be sounded simultaneously. The brain's task is to attempt to parse the frequencies into sound sources. We will focus on the puzzle of virtual pitch and the missing fundamental, which demonstrates this constructive aspect of auditory perception.

Most periodically vibrating objects to which we attribute pitch, including the human vocal folds and the strings of musical instruments, vibrate at several sinusoidal component frequencies simultaneously (Figure 1). Typically, these frequencies or partials are approximately

integer multiples (*harmonics*) of the fundamental frequency, and the complex is called a *harmonic spectrum*. While each of these frequencies sounded alone would evoke a *spectral pitch*, when sounded simultaneously they perceptually fuse and collectively evoke a singular *periodicity pitch*. For harmonic spectra, the periodicity pitch can be matched to the spectral pitch of a pure tone sounded alone at the fundamental frequency (Stumpf, 1898; Thurlow & Rawlings, 1959; DeWitt & Crowder, 1987; Parncutt, 1989). This is not surprising because the fundamental is the most intense harmonic in most natural harmonic sources. However, one can remove the fundamental frequency from a harmonic spectrum and still hear it as the predominant *virtual pitch* (Terhardt, 1974), a phenomenon known as the *missing fundamental*. The perception of a virtual pitch when the fundamental frequency is missing is the central puzzle that has motivated research in pitch perception since Helmholtz (1863/1954) and is the most important empirical constraint on any model of pitch.
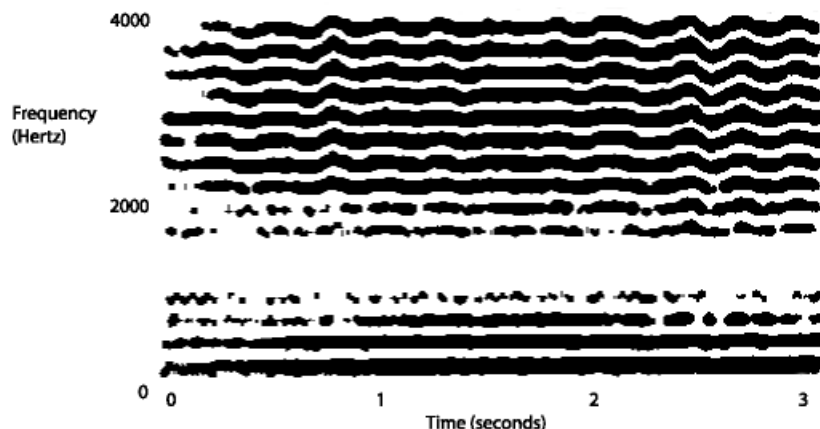

Figure 1: Harmonic structure in the human voice. When sustaining a single pitch, the human vocal folds vibrate at a fundamental frequency (220 Hertz) and at integer multiples of this frequency (440, 660, and so forth). The pitch of such harmonic spectra is matched to that of a sine wave tone at the fundamental frequency. In this case, the relative intensities of the higher order harmonics have been modified by the shape of the vocal tract, which determines the vowel quality of the pitch (/i/).

Helmholtz attributed the missing fundamental to nonlinear distortion in peripheral hearing mechanisms. This was a plausible idea because difference frequencies can be introduced into a sound spectrum by nonlinear distortion, and the fundamental frequency is the difference between the frequencies of adjacent harmonics (see Green, 1976). However, the evidence indicates that it is an illusory percept resulting from the brain's attempt to reconstruct a coherent harmonic spectrum. In this respect, pitch perception is similar to the perception of illusory contours and other examples of constructive visual perception (see Palmer, this volume). Three classes of evidence demonstrate that virtual pitch cannot be explained by nonlinear distortion alone. First, a virtual pitch cannot be masked by noise within the fundamental frequency's *critical band*, the range in which frequencies interact (see Buus, this volume), but can only be

masked by noise within the critical bands of the harmonics from which it is computed (Licklider, 1954). Second, virtual pitch can be induced centrally via dichotic presentation of subsets of harmonics (Houtsma & Goldstein, 1972). Finally, when the partials are not among the first ten harmonics of the lowest frequency, the predominant virtual pitch corresponds neither to the fundamental nor to other distortion products (Hermann, 1912; de Boer, 1956; Schouten, Ritsma & Cardozo, 1962).

This last piece of evidence has been the most challenging to explain. For example, a tone consisting of partials at 800, 1000, and 1200 Hz has a predominant periodicity pitch at 200 Hz. Here 200 Hz is both the fundamental (the highest common divisor) and the difference frequency (a distortion product). However, a tone consisting of partials at 850, 1050 and 1250 Hz has neither a pitch at 50 Hz (the fundamental frequency) nor at 200 Hz (the difference frequency). Its pitch is somewhat ambiguous but is most closely matched to around 210 Hz. Wightman (1973a) attempted to explain this in terms of the temporal fine structure (i.e., the shape) of the time-domain waveform. He averaged the distances between salient peaks in the waveform resulting from adding the partials in cosine phase, and found that the resulting period predicted the pitch. Unfortunately, the temporal fine structure of the waveform depends upon the relative phases of the partials, whereas the pitch percept does not (Patterson, 1973; Green, 1976).

Most subsequent theories have postulated a pattern recognition system that attempts to match the signal to a noisy or fuzzy harmonic template (e.g., Goldstein, 1973; Terhardt, 1972, 1974, 1979; Wightman, 1973b). The closest match of 850, 1050, and 1250 Hz is to a harmonic template with 210 Hz as the fundamental, whose fourth, fifth and sixth harmonics are 840, 1050, and 1260 Hz. (Harmonics beyond the tenth play little role in pitch perception; hence the pattern matching process looks for the best match to low order harmonics.) Some models have attempted to demonstrate how the to-be-matched harmonic template is learned through self-organizing neural net mechanisms (Cohen et al., 1995). Others have attempted to account for the brain's reconstruction of the harmonic spectrum using the probability distributions of temporal firing characteristics of phase-locked neurons.

Pitch Height and Pitch Class

Traditionally pitch has been described as varying along a single dimension from low to high, called *pitch height*. Along this dimension, pitch is a logarithmic function of frequency. The Western equal-tempered tuning system divides each frequency doubling (*octave*) into twelve equally spaced steps (*semitones*) on a logarithmic scale, with one note being $2^{1/12}$ (about 1.06) times the frequency of the preceding note (Table 1, columns 1 and 3). Such a scale preserves the interval sizes under transformations, and reflects the importance of relative rather than absolute pitch perception in music (Attneave & Olson, 1971).

However, this single dimension is not sufficient to describe our mental representation of pitch. Another dimension called *tone chroma* or *pitch class* underlies *octave equivalence*, the perceived similarity of tones an octave apart. Octave equivalence motivates the pitch naming system in Western music, such that tones an octave apart are named with the same letter (e.g. C, D, E) or syllable (e.g. do, re, mi). Shepard (1964) demonstrated this second dimension by generating tone complexes with octave-spaced frequencies whose amplitudes are largest in the middle frequency range and gradually diminish to the threshold of hearing in the high and low

frequency ranges. Such tone complexes are known as Shepard tones and have a very salient pitch class but an ambiguous pitch height. The perceived direction of motion between two Shepard tones is based on the distance between the two pitch classes. When the distance in either direction between the two complexes is the same (the interval of a tritone, C to F# for example), the percept is ambiguous, although there are consistent individual differences in how these tone pairs are perceived (Deutsch, 1986, 1987, 1991; Repp, 1994). This circular dimension of pitch class can be combined with the linear dimension of pitch height to create a helical representation of pitch (Figure 2). Additional geometric models of musical pitch include the *circle of fifths* (Figure 3) as a third dimension (see Shepard, 1982). However, even these additional dimensions do not fully capture the perceived relatedness between pitches in music, among other reasons because of the temporal order asymmetries found between pitches in musical contexts (Krumhansl, 1979, 1990). This is a general concern for spatial representations of similarity given that geometric distances must be symmetric (Tversky, 1977; Krumhansl, 1978).

Pitch	Interval with C	Frequency relationship with C (equal tempered)	Frequency ratio with C (approx.)	Diatonicity in C Major	Function in C Major	Chord in C Major
C	unison (octave)	262 Hz (524 Hz)	1:1 (2:1)	diatonic	tonic	C Major (I), CDE
C#, Db	minor second	$262 (2^{1/12}) = 278$ Hz	16:15	non-diatonic		
D	major second	$262 (2^{2/12}) = 294$ Hz	9:8	diatonic	supertonic	d minor (ii), DFA
D#, Eb	minor third	$262 (2^{3/12}) = 312$ Hz	6:5	non-diatonic		
E	major third	$262 (2^{4/12}) = 330$ Hz	5:4	diatonic	mediant	e minor (iii), EGB
F	perfect fourth	$262 (2^{5/12}) = 350$ Hz	4:3	diatonic	subdominant	F Major (IV), FAC
F#, Gb	tritone	$262 (2^{6/12}) = 371$ Hz	45:32	non-diatonic		
G	perfect fifth	$262 (2^{7/12}) = 393$ Hz	3:2	diatonic	dominant	G Major (V), GBD
G#, Ab	minor sixth	$262 (2^{8/12}) = 416$ Hz	8:5	non-diatonic		
A	major sixth	$262 (2^{9/12}) = 440$ Hz	5:3	diatonic	submediant	a minor (vi), ACE
A#, Bb	minor seventh	$262 (2^{10/12}) = 467$ Hz	16:9	non-diatonic		
B	major seventh	$262 (2^{11/12}) = 495$ Hz	15:8	diatonic	leading tone	b diminished (vii°), BDF

Table 1: The twelve pitch classes and intervals within a single octave. The Western system divides the octave into twelve logarithmically spaced pitch classes, seven of which have specific functions as the diatonic notes in a particular key. Different combinations of two pitches give rise to twelve kinds of intervals, the consonance of which is correlated with how well the frequency ratio can be approximated by a simple integer ratio. Within a key, the seven diatonic chords are formed by combining three diatonic pitches in thirds. (Note that the choice of C as the reference pitch for this table is arbitrary.)
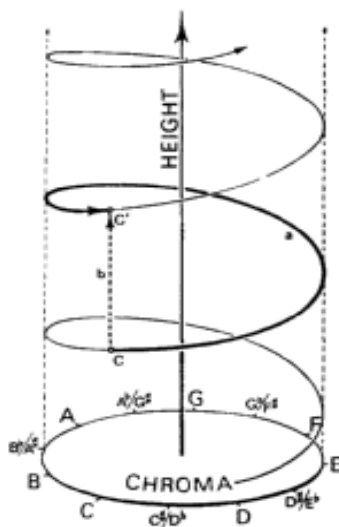
Figure 2: The pitch helix. The psychological representation of musical pitch has at least two dimensions, one logarithmically scaled linear dimension corresponding to pitch height and another circular dimension corresponding to pitch class or tone chroma. From Shepard (1965). *Copyright ©1965 by Stanford University Press. Reprinted with permission.*
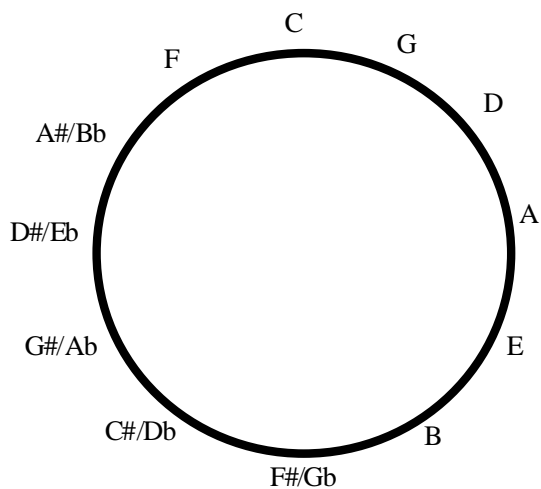

Figure 3: The circle of fifths. The circle of fifths represents the similarity between the twelve major keys, with any two adjacent keys on the circle differing in only one pitch. It also represents the sequential transition probabilities between major chords. For example, a C-Major chord is very likely to be followed by a G-Major or F-Major chord, and very unlikely to be followed by an F#-Major chord.

Pitch Categorization, Relative Pitch, and Absolute Pitch

Listeners are able to detect small differences in frequency, differences as small as one-half of one percent (Weir et al., 1977). The pitch class categories into which we divide the dimension of frequency are much larger; a semitone is a frequency difference of about six percent. Some musicians perceive these intervals categorically (Burns & Ward, 1978; Siegel & Siegel, 1977a, b). This kind of categorical perception is characterized by clear category boundaries in a categorization task and an enhanced ability to discriminate stimuli near or across category boundaries, relative to stimuli in the center of a category (Studdert-Kennedy et al., 1970). Pitch classes differ from stronger instances of categorical perception, as in speech, in that it is still possible to discriminate between different examples within the same category (see Jusczyk & Luce, this volume). For example, Levitin (1996, 1999) has pointed out that while musicians do assign non-focal pitches (those near the boundary) to the nearest category, they will rate the focal pitch of the category as the best member or prototype and give lower ratings to pitches higher and lower than this reference pitch.

Although few listeners are able to assign names consistently to pitches, most people have the ability known as *relative pitch*. This allows them to recognize the relationship between two pitches and to learn to name one pitch if given the name of the other. Listeners with *absolute pitch* can identify the names of pitches in the absence of any reference pitch. Considering the helical model of pitch height and pitch class (Figure 2), it is as if the mental representation of the pitch class circle does not contain set labels for the listener with relative pitch but does for the listener with absolute pitch. Despite the popular misnomer of "perfect" pitch, absolute pitch is not an all-or-none phenomenon; many musicians display absolute pitch for their primary instrument timbre only (see Miyazaki, 1989), and many musicians display absolute pitch for particular pitches only, such as the 440-Hertz A to which orchestras tune (see Bachem, 1937). Furthermore, many musicians with relatively strong absolute pitch identify the white notes of the piano (C, D, E, and so on) better than the black notes (C#, D#, and so on). This may be due either to the fact that children typically are exposed to the white notes of the piano first in the course of their musical instruction (Miyazaki, 1988), the prevalence of these pitches in music generally, or the differences in the names we give to the black and white notes of the piano (Takeuchi & Hulse, 1991). The first notion is consistent with the critical period hypothesis for absolute pitch, namely that children will acquire the ability if taught to name pitches at an early age (for review see Takeuchi & Hulse, 1993).

What is sometimes called latent absolute pitch ability has received additional attention. Levitin (1994) designed a study in which participants sang the opening line of a familiar popular song, using the album cover as a visual cue. Twelve percent of these individuals sang in the key of the original song and fourty-four percent came within two semitones of the original key. Levitin suggests that absolute pitch is actually two separate abilities, *pitch memory*, a common ability in which pitch information is stored veridically along with relational information, and *pitch labeling*, a less common ability in which the listener has verbal labels to assign to pitch categories.

Consonance and Dissonance

Two pitches, whether played simultaneously or sequentially, are referred to as an *interval*. Consonance and dissonance refer to particular qualities an interval can possess. *Tonal consonance* or *sensory consonance* refers to the degree to which two tones sound smooth or fused, all else being equal. *Musical consonance* refers to a similar quality as determined by a specific musical context and the musical culture of the listener more generally (Krumhansl, 1991). The opposite qualities are tonal and musical dissonance, the degree of perceived roughness or distinctness. Intervals that can be expressed in terms of simple frequency ratios, such as unison (1:1), the octave (2:1), perfect fifth (3:2), and perfect fourth (4:3) are regarded as the most consonant (Table 1, columns 1-4). Intermediate in consonance are the major third (5:4), minor third (6:5), major sixth (5:3), and minor sixth (8:5). The most dissonant intervals are the major second (9:8), minor second (16:15), major seventh (15:8), minor seventh (16:9), and the tritone (45:32).

Helmholtz (1863/1954) proposed that tonal consonance was related to the absence of interactions or beating between the harmonic spectra of two pitches, an idea that was supported in the model of Plomp and Levelt (1965). They calculated the dissonance of intervals formed by complex tones based on the premise that dissonance would result when any two members of the pair of harmonic spectra lay within a critical band. The model's measurements predicted that the most consonant intervals would be the ones that could be expressed with simple frequency ratios, which has been confirmed by psychological study (Vos & van Vianen, 1984; DeWitt & Crowder, 1987).

Scales and Tonal Hierarchies of Stability

As mentioned previously, our perception of pitch can be characterized by two primary dimensions, pitch height and pitch class. These two dimensions roughly correspond to the first and second of Dowling's (1978) four levels of abstraction for musical scales. The most abstract level is the *psychophysical scale*, which relates pitch in a logarithmic manner to frequency. The next level is the *tonal material*, the pitch categories into which the octave is divided, for example the twelve pitch class categories of the Western system. For specific pieces of music, two additional levels are added. The third level in Dowling's scale scheme is the *tuning system*, a selection of five to seven categories from the tonal material to be used in a melody. In Western classical music, this corresponds to the selection of the seven notes of a major or minor scale, derived by a cycle of [2, 2, 1, 2, 2, 2, 1] semitones for the major (e.g. C D E F G A B C) and [2, 1, 2, 2, 1, 2, 2] semitones for the natural minor (e.g. A B C D E F G A). Such scales consisting of a series of five whole tones and two semitones are *diatonic*, and within a musical context the members of the scale are the *diatonic notes* (Table 1, column 5). Lastly, the fourth level is *mode*. In this level a tonal hierarchy is established, with particular notes within the tuning system given more importance or stability than others (Table 1, column 6). These last two levels go hand-in-hand for Western listeners, as a particular hierarchy of stability is automatically associated with each tuning system. Musical works or sections thereof written primarily using one particular tuning system and mode are said to be in the *key* that shares its name with the first note of the scale. While the psychophysical scale is universal, tonal material, tuning systems, and modes reflect both psychoacoustic constraints and cultural conventions. We will return to this issue in the final section. For a very thorough exploration of scales both Western and non-Western, the reader is directed to the review by Burns (1999).

Within a tonal context such as the diatonic scale, the different pitches are not of equal importance but rather are differentiated in a hierarchy of stability, giving rise to the quality of *tonality* in Western and many genres of non-Western music. This stability is a subjective property that is a function of both the salience of the tone in the context as well as the extent to which it typically occurs in similar contexts. One method that has illustrated such hierarchies of stability is the probe tone method devised by Krumhansl and colleagues (see Krumhansl, 1990). In the original study using this technique (Krumhansl & Shepard, 1979), an ascending or descending major scale was played (the tonal context) and then was followed by one of the twelve chromatic notes (the probe tone), and the participants were asked to rate how well the final tone completed the context. Listeners with musical training rated diatonic tones (the scale tones) more highly than they did nondiatonic tones (the non-scale tones). The ratings produced by the musicians also suggested that they were affected by their knowledge of how each particular tone functions within the tonality established by the scale. For a major tonal context (e.g. C Major), the tonic received the highest rating, followed by the dominant (G), mediant (E), subdominant (F), submediant (A), supertonic (D), leading tone (B), and then the nondiatonic tones (Figure 4, upper left; also Table 1, columns 5-6). A similar pattern held for minor tonal contexts, with the primary exception that the mediant (E-flat in a c minor context) is second in rating to the tonic. This is consistent with the importance of the relative major tonality when in a minor context. Although the non-musicians in this study based their judgments primarily on pitch height, other studies have suggested that non-musicians also perceive tonal hierarchies (Cuddy & Badertscher, 1987; Hébert et al., 1995).

Krumhansl and Kessler (1982) used the set of probe tone ratings for each key, collectively called a *key profile* (Figure 4, upper left), to create a set of measurements of key distance, allowing the twenty-four keys to be represented in a multidimensional space. The correlations between the different key profiles (Figure 4, lower left) were in agreement with what one would predict from music-theoretical concepts of key distance. The analysis algorithm solved the set of key profiles correlations in four dimensions. Although most four-dimensional solutions are difficult to visualize, undermining their utility, patterns in these particular data allowed for it to be represented a different way. Because two dimensional plots of the first and second dimensions and of the third and fourth dimensions were roughly circular (Figure 4, upper right), the data could be represented as a three-dimensional torus, in which the angles of the two circular representations were translated into the two angular positions on the torus, one for each of its circular cross-sections (Figure 4, lower right). In this representation, the major and minor keys can be visualized spiraling around the outer surface of the torus. The order of both the major and minor key spirals are that of the circle of fifths, and the relative position of the two spirals reflects the similarity between relative keys (sharing the same diatonic set, such as C Major and a minor) and parallel keys (sharing the same tonic, such as C Major and c minor).
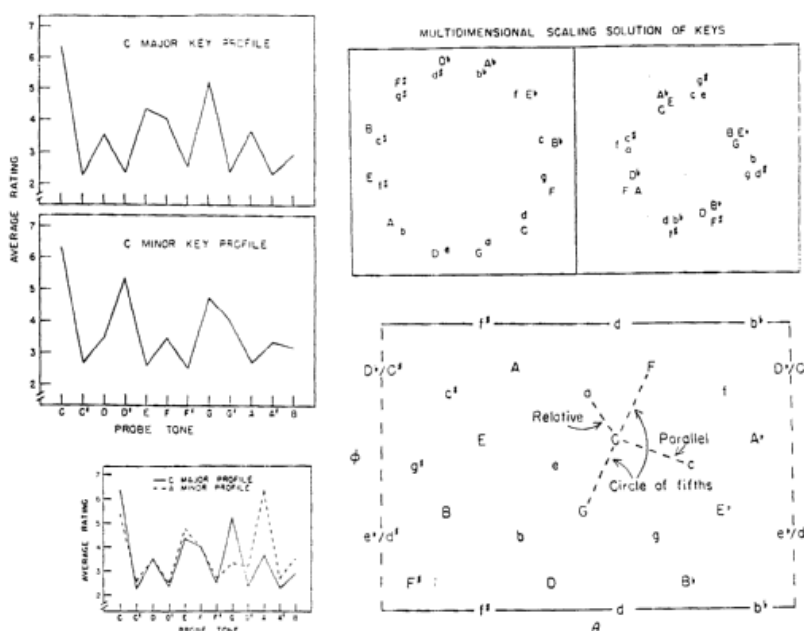
Figure 4: Tonal hierarchies and keys. A musical context establishes a hierarchy of stability for the twelve pitch classes, with characteristic hierarchies for major and minor keys. Diatonic notes are regarded as more stable than non-diatonic notes, with the tonic and dominant as the most stable (upper left). Correlations between the twenty-four key profiles (lower left) produce a multidimensional scaling solution in four dimensions (upper right), which can be represented as a flattened torus (lower right). See text for further discussion. From Krumhansl and Kessler (1982). *Copyright ©1982 by the American Psychological Association. Reprinted with permission.*

Tonal hierarchies for major and minor keys have played a role in numerous other experiments. They are predictive of the response time needed to make a key-membership judgment (Janata & Reisberg, 1988), melodic expectation (Schmuckler, 1989), and judgments of phrase endings (Palmer & Krumhansl, 1987a, 1987b). They are also employed in the Krumhansl-Schmuckler key-finding algorithm (described in Krumhansl, 1990, chapter 4), which calculates a twelve-dimensional vector for a presented piece of music and correlates it with each of the 24 twelve-dimensional tonal hierarchies. The probe tone method has also been used to study the tonal hierarchies of two non-Western systems, the North Indian system (Castellano et al., 1984) and the Balinese system (Kessler et al., 1984).

Related to the probe tone method is a similar technique in which a musical context is followed by two tones, which participants are asked to rate with respect to similarity or good continuation. Ratings are higher when the pair includes a stable pitch in the tonal hierarchy, and furthermore this effect is stronger when the stable pitch is the second note in the pair (Krumhansl, 1990). This results in the observation that the ratings between one tone pair ordering and its reverse are different, and these differences are greatest for pairs in which only one tone is stable in the preceding context. Multidimensional scaling was performed on these data as well, but rather than measuring the similarities (correlations) between the twenty-four key profiles, the similarities in this case were those between the twelve tones of a single key. The

analysis found a three-dimensional solution in which the points representing the twelve pitches roughly lie on the surface of a cone, with the tonal center at the vertex. One factor clearly represented by this configuration is pitch class; the tones are located round the cone in order of their positions on the pitch class circle. A second factor is the importance of the pitches in the tonal hierarchy; they are arranged such that tones with high positions in the hierarchy are located near the vertex, closer to the tonal center and to each other than the remaining less stable tones.

Chords and Harmonic Hierarchies of Stability

Harmony is not only a product of a tonal hierarchy of stability for pitches within a musical context but also a harmonic hierarchy of stability for chords. A *chord* is simply the simultaneous (or sequential) sounding of three or more notes, and the Western system is built particularly on the triads within the major and minor keys. A *triad* is a chord consisting of three members of a scale, with each pair spaced by the interval of a major or minor third. Thus there are four types of triad: major, minor, diminished, and augmented, depending upon the particular combination of major and minor thirds used. In a major or minor key, the kind of triad built upon each scale degree will depend upon the particular series of semitones and whole tones that make up the scale (Table 1, column 7). For example, in the key of C Major the seven triads are C Major (I), d minor (ii), e minor (iii), F Major (IV), G Major (V), a minor (vi), and b diminished (vii°). The tonic (I), dominant (V), and subdominant (IV) are considered the most stable chords in the key by music theorists, followed by ii, vi, iii, and vii°. (Note that the use of the word "harmonic" in the sense of musical harmony is distinct from the acoustic sense, as in "harmonic spectra.")

This hierarchy of harmonic stability has been supported by psychological studies as well. One approach involves collecting ratings of how one chord follows from another. For example, Krumhansl, Bharucha, and Kessler (1982) used such judgments to perform multidimensional scaling and hierarchical clustering techniques. The psychological distances between chords reflected both key membership and stability within the key; chords belonging to different keys grouped together with the most stable chords in each key (I, V, and IV) forming an even smaller cluster. Such rating methods also suggest that the harmonic stability of each chord in a pair affects its perceived relationship to the other, and this depends upon the stability of the second chord in particular (Bharucha & Krumhansl, 1983). Additionally, this chord space is plastic and changes when a particular tonal context is introduced; the distance between the members of a particular key decreases in the context of that key (Bharucha & Krumhansl, 1983; Krumhansl, Bharucha, & Castellano, 1982).

Convergent evidence is provided from studies of recognition memory, in which two chord sequences are presented and participants must decide if they are the same or different, or in the case where all sequences differ, judge at which serial position the change occurred. In such studies, tonal sequences (reflecting a tonal hierarchy) are more easily encoded than are atonal sequences, nondiatonic tones in tonal sequences are often confused with more stable events, and stable chords are easily confused with each other (Bharucha & Krumhansl, 1983). Additionally, the probability of correctly detecting a change in a particular chord is systematically related to that chord's role in the presented tonal context (Krumhansl, Bharucha, & Castellano, 1982). Finally, nondiatonic chords in tonal sequences disrupt the memory for prior and subsequent chord events close in time (Krumhansl & Castellano, 1983).

There are some compelling similarities between the cognitive organization of chords and that of tones described in the previous section. For both tones and chords, a musical context establishes a hierarchy of stability in which some events are considered more important or stable than others. In both cases, the psychological space representing tones or chords is modified in a musical context in three principal ways (Bharucha & Krumhansl, 1983; Krumhansl, 1990). First, an important event in the hierarchy of stability is considered more similar to other instances of itself than is a less important event (*contextual identity*). Second, two important events in the hierarchy of stability are considered more similar to each other than are less important events (*contextual distance*). Third, the asymmetry in a pair of similarity judgments is largest when the first event is less important in the hierarchy and the second event is more important (*contextual asymmetry*). These results support the idea that stable tones and chords in tonal contexts serve as cognitive reference points (Rosch, 1975a), and are compelling examples of how musical organization can reflect domain-general principles of conceptual representation.

Harmonic Perception, Representation, and Expectation

Implicit knowledge of the relationships between the chords in Western music has also been shown in the chord priming paradigm of Bharucha and colleagues (Bharucha & Stoeckig, 1986, 1987; Tekman & Bharucha, 1992, 1998). In each trial of this paradigm the participants are presented with two chords, a prime and a target, and are required to respond to some aspect of the target. The task is typically to identify whether the target chord is in tune or mistuned, although onset asynchrony (Tillmann & Bharucha, under review) and phoneme discrimination tasks (Bigand et al., under review) have been used as well. The variable of interest, however, is the harmonic relationship between the two chords, which is related to the probability of these events occurring in sequence with each other. The results of the original study (Bharucha & Stoeckig, 1986) indicated that responses to tuned target chords that were in a close harmonic relationship with the prime were faster and more accurate than responses to such chords distantly related to the prime. The data also revealed a response bias in that participants were more likely to judge a related target chord as more consonant; in an intonation task a close target is likely to be judged as tuned, whereas a distant target is likely to be judged as mistuned. Such priming is generated at a cognitive level, via activation spreading through a representation of tonal relationships, rather than by perceptual priming of specific frequencies (Bharucha & Stoeckig, 1987), and occurs automatically even when more informative veridical information about the chord progression has been made explicitly available (Justus & Bharucha, in press), suggesting that the mechanisms of priming are informationally encapsulated to some degree (see Fodor, 1983, 2000). Both musicians and non-musicians alike demonstrate harmonic priming, and evidence from self-organizing networks suggests that this implicit tonal knowledge may be learned via passive exposure to the conventions of Western music (Bharucha, 1987; Tillmann et al., 2000).

Global harmonic context can influence the processing of musical events even when the local context is precisely the same. Bigand and Pineau (1997) created pairs of eight-chord sequences in which the final two chords were identical for each pair. The first six chords, however, established two different harmonic contexts, one in which the final chord was highly expected (a tonic following a dominant) and the other in which the final chord was less highly expected (a subdominant following a tonic). Target chords were more easily processed in the

former case, indicating an effect of global harmonic context (Figure 5). Furthermore, different contexts can be established by harmonic structure occurring several events in the past. Bigand et al. (1999) found that target chords are processed more efficiently when they are more closely related to the overarching harmonic context (as determined by the harmony of a preceding phrase), even when all of the chords in the second phrase are identical. Tillmann and colleagues (Tillmann et al., 1998; Tillmann & Bigand, in press) have compared the mechanisms of harmonic priming and semantic priming. They note that while two distinct mechanisms have been proposed for language, one from spreading activation and another from structural integration, the former alone can account for reported harmonic priming results.
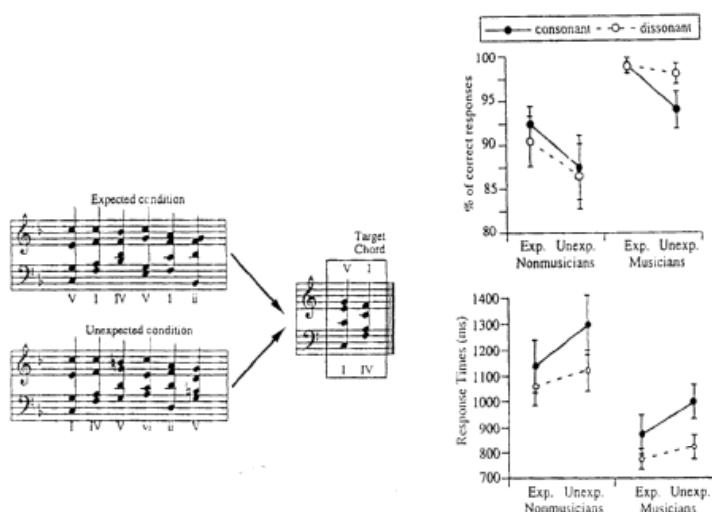

Figure 5: Chord priming by a global harmonic context. Musical contexts establish expectations for subsequent events, based on the musical schema of the listener. A target chord (F Major in the figure) is processed more efficiently at the end of a context that establishes it as the most stable event (the tonic chord) than a context that establishes it as a moderately stable event (the subdominant chord), even when the immediately preceding chord (C Major in the figure) is precisely the same. This is evidenced by both error rates and response times, and is true of both musician and non-musician listeners. From Bigand et al. (1999). *Copyright ©1999 by the American Psychological Association. Reprinted with permission.*

Melodic Perception, Representation, and Expectation

The composition of a melody generally reflects the tonal hierarchy of stability, frequently returning to a set of stable reference points. The tonal hierarchy affects the listener's melodic expectation; less stable tones within a tonal context are usually immediately followed by nearby more stable tones. Bharucha (1984a, 1996) has referred to this convention and the expectation for it to occur as *melodic anchoring*. Conversely, different melodies will recruit a particular tonal hierarchy to varying degrees depending on its fit with the structure of the melody (Cuddy, 1991), requiring a degree of tonal bootstrapping on the part of the listener.

An additional constraint upon melodies is that the individual notes of the melody must be *streamed* or perceptually grouped as part of the same event unfolding over time, and the rules that determine which events will and will not be grouped together as part of the same melody are explained in part by the Gestalt principles of perceptual organization (Bregman, 1990; Deutsch, 1999a; McAdams & Drake, this volume). For example, whether a series of tones is heard as a single melody or is perceptually streamed into two simultaneous melodies depends on the tempo, the similarity of the tones in pitch height, and other factors including timbral similarity. Composers often follow compositional heuristics such as an avoidance of part-crossing when composing melodies, helping the perceiver stream the voices (see Huron, 1991). This is of particular importance for counterpoint and other forms of polyphony, in which multiple voices singing or playing simultaneously must be streamed correctly by the listener if they are to be perceived as distinct events. Conversely, composers can exploit auditory streaming to create virtual polyphony, the illusion that simultaneous voices are present rather than one. For example, the solo string and woodwind repertoire of the Baroque period often contains fast passages of notes alternating between different registers, creating the impression that two instruments are playing rather than one.

Similar principles also can explain higher order levels of melodic organization. Narmour (1990) has proposed a theory of melodic structure, the implication-realization model, which begins with elementary Gestalt principles such as similarity, proximity, and good continuation. The responses of listeners in continuity-rating and melody-completion tasks have provided empirical support for some of these principles (Krumhansl, 1995; Cuddy & Lunney, 1995; Thompson et al., 1997; see also Schellenberg, 1996, 1997). According to Narmour, these basic perceptual rules generate hierarchical levels of melodic structure and expectation when applied recursively to larger musical units.

Another body of research has examined the memory and mental representation of specific melodies. Studies of melody recognition when transposed to a new key suggest that melodic fragments are encoded with respect to scales, tonal hierarchies, and keys (Cuddy & Cohen, 1976; Dewar et al., 1977; Cuddy et al., 1979, 1981; Cuddy & Lyons, 1981). Melodies are processed and encoded not only in terms of the musical scale in which they are written, but also independently in terms of their *melodic contour*, the overall shape of the melody's ups and downs. When discriminating between atonal melodies, in which there is no tonal hierarchy, listeners rely mainly on the melodic contour (Dowling & Fujitani, 1971). Furthermore, within tonal contexts, melodies and their tonal answers (transpositions that alter particular intervals by semitones to preserve the key) are just as easily confused as exact transpositions (Dowling, 1978). One explanation of this result is that the contour, which is represented separately from the specific interval information, is processed relative to the framework provided by the scale.

TIME

Tempo

Among the temporal attributes of music are tempo, rhythmic pattern, grouping, and meter. The *tempo* describes the rate at which the basic pulses of the music occur. Several lines of evidence suggest a special perceptual status for temporal intervals ranging from approximately 200 to 1800 ms, and in particular those ranging from approximately 400 to 800 ms. Both the *spontaneous tempo* and the *preferred tempo*, those at which humans prefer to produce and hear an isochronous pulse, are based upon a temporal interval of about 600 ms (Fraisse, 1982). The range of about 200 to 1800 ms also describes the range of accurate synchronization to a presented isochronous pulse, a task at which we become proficient early (Fraisse et al., 1949) and which we find easier than reacting *after* each isochronous stimulus (Fraisse, 1966).

Rhythmic Pattern

A *rhythmic pattern* is a short sequence of events, typically on the order of a few seconds, and is characterized by the periods between the successive onsets of the events. The inter-onset periods are typically simple integer multiples of each other; 85 to 95 percent of the notated durations in a typical musical piece are of two categories in a ratio of either 2:1 or 3:1 with each other (Fraisse, 1956, 1982). The limitation of durations to two main categories may result from a cognitive limitation; even musically trained subjects have difficulty distinguishing more than two or three duration categories in the range below two seconds (Murphy, 1966). Listeners distort near-integer ratios towards integers when repeating rhythms (Fraisse, 1982), and musicians have difficulty reproducing rhythms that cannot be represented as approximations of simple ratios (Fraisse, 1982; Sternberg et al., 1982). Rhythms of simple ratios can be easily reproduced at different tempi, which is not true for more complex rhythms (Collier & Wright, 1995). However, the simplicity of the ratio cannot explain everything. Povel (1981) found that even if the ratios in a rhythmic pattern are integers, participants may not appreciate this relationship unless the structure of the pattern makes this evident. For example, a repeating sequence with intervals of 250-750-250-750 ms is more difficult than 250-250-250-750 ms, a pattern in which the 1:3 ratio between the elements of the pattern is emphasized by the pattern itself.

Grouping

A *group* is a unit that results from the segmentation of a piece of music, much as text can be segmented into sections, paragraphs, sentences, phrases, words, feet, and syllables. Rhythmic patterns are groups containing subordinate groups, and they can be combined to form superordinate groups such as musical phrases, sequences of phrases, sections, and movements. Lerdahl and Jackendoff (1983) proposed that the psychological representation of a piece of music includes a hierarchical organization of groups called the *grouping structure*. Evidence supporting grouping mechanisms was found by Sloboda and Gregory (1980), who demonstrated that clicks placed in a melody were systematically misremembered as occurring closer to the boundary of the phrase than they actually did, just as in language (Garrett et al., 1966). Furthermore, there are constraints on what can constitute a group. For example, a preference for listening to groups that end with a falling pitch contour and long final duration is present as early as four months of age (Krumhansl & Jusczyk, 1990; Jusczyk & Krumhansl, 1993).

Grouping can occur perceptually even when there is no objective basis for it, a phenomenon called *subjective rhythmization*. Within the range of about 200 to 1800 ms intervals, an isochronous pattern will appear to be grouped in twos, threes, or fours (Bolton, 1894), and when asked to synchronize with such a pattern subjects illustrate their grouping by lengthening and accenting every other or every third event (MacDougall, 1903). Grouping is not independent of tempo; groups of larger numbers are more likely at a fast tempo (Bolton, 1894; Fraisse, 1956; Hibi, 1983; Nagasaki, 1987a, 1987b; Peters, 1989). Rhythmic pattern also affects grouping; events separated by shorter intervals in a sequence will group into a unit the length of a longer interval (Povel, 1984). Finally, grouping is qualitatively different at different levels of the hierarchy. Levels of organization less than about five seconds form groups within the psychological present (Fraisse, 1982; see also Clarke, 1999).

For both grouping and meter, Lerdahl and Jackendoff (1983) propose a set of well-formedness rules and preference rules for deciding which perceptual interpretation to assign to a particular musical passage. The well-formedness rules are absolute, while the preference rules are like the Gestalt principles in that they are *ceteris paribus* rules (all else being equal). The empirical worth of the grouping rules has not been subject to a large amount of study, with the exception of work by Deliège (1987).

Meter

Meter is a hierarchical organization of beats. The first essential characteristic of meter is isochrony; the beats are equally spaced in time, creating a pulse at particular tempo (Povel, 1984). A *beat* has no duration and is used to divide the music into equal *time-spans*, just as in geometry a point divides a line into segments. The beat is thus not a feature of the raw musical stimulus, but something the listener must infer from it. For example, if a new event occurs almost every second, a beat is perceived every second, whether or not there is an event onset.

Povel (1984) proposed a model of meter in which the most economical *temporal grid* is chosen. In this model a temporal grid is a sequence of isochronous intervals with two parameters, duration (establishing a tempo) and phase. Each interval in a rhythmic pattern is a possible grid duration. The temporal grid is chosen based on the degree to which it fulfills three requirements: fixing the most elements in the rhythmic pattern, not fixing many empty points in time, and specifying the non-fixed elements within the grid. Rhythms can be metrical to varying degrees. The strength of the meter and the ease of reproducibility are related, which led Essens and Povel (1985) to suggest that highly metrical rhythms induce an internal clock that helps the listener encode the rhythm in terms of the meter. Metrical strength is also associated with an asymmetry in discrimination; it is easier to discriminate between two similar rhythmic patterns when the more strongly metrical one is presented first (Bharucha & Pryor, 1986).

The second characteristic of meter is a hierarchy of perceived stress, or a *metrical hierarchy*, such that events occurring on some beats are perceived to be stronger and longer than those on the others, even if these events are not acoustically stressed. A metrical hierarchy arises when there is more than one level of metrical organization (Lerdahl & Jackendoff, 1983). The level of the hierarchy at which the isochronous pulse is the most salient is called the basic metrical level or *tactus*, and this level is often chosen such that the time span between tactus beats is between 200 and 1800 ms, the tempo range that is processed most accurately. The two

most common meters are duple (alternating stressed and unstressed beats, as in a march) and triple (stressed following by two unstressed, as in a waltz). In duple meter, the tactus has two beats per cycle and the first superordinate level has one beat (the stressed beat or downbeat) per cycle. There may be subordinate metrical levels as well, arising from subdivisions of each beat into two or three. These different levels create a hierarchy of importance for the different beats in the measure; beats that are represented at higher hierarchical levels are regarded as stronger or more stable than the others.

Empirical support for the perception of metrical hierarchies comes from experiments in which participants judged the completeness of music ending on different beats of the meter (Palmer & Krumhansl, 1987a, 1987b) as well as experiments in which they rated the appropriateness of probe tones entering at different metrical positions or decided if the probe tones entered in the same metrical position as they had before (Palmer & Krumhansl, 1990). However, Handel (1998) showed that information about meter is not used consistently when participants discriminate between different rhythms when the figural (grouping) organization is the same. He questions whether the concept of meter is necessary and suggests that the apparent discrepancy between the importance of meter in rhythm production and perception may be resolved by noting that metrical rhythms are better reproduced because they are easier, and not because they are metrical.

Event Hierarchies and Reductions

In addition to the grouping and metrical hierarchies, Lerdahl and Jackendoff (1983) propose two kinds of *reduction* in *A Generative Theory of Tonal Music (GTTM)*. Reductions for music were first proposed by musicologist Heinrich Schenker (1935), who was able to capture the elaboration of underlying structures in the musical surface. The concept of reduction in general implies that the events in music are heard in a hierarchy of relative importance. Such event hierarchies are not to be confused with the tonal hierarchies described in the preceding section, although the two interrelate in important ways (Bharucha, 1984b; Deutsch, 1984; Dowling, 1984). *Event hierarchies* refer to the temporal organization of a specific piece of music, with more important musical events represented higher in the hierarchy, while *tonal hierarchies* refer to the organization of categories of pitch events, with some pitch classes being regarded as more stable in the context. A tonal hierarchy plays a role in the organization of an event hierarchy. The two reductions of *GTTM* are time-span reduction and prolongational reduction. The *time-span reduction* relates pitch to the temporal organization provided by meter and grouping; this reduction is concerned with relative stability within rhythmic units. The *prolongational reduction* relates harmonic structure to the information represented by the time-span reduction; this reduction is concerned with the sense of tension and relaxation in the music (also see Krumhansl, 1996). *GTTM* adopts a tree structure notation for these reductions, which represents how one event is subordinate to or an elaboration of the other. Branches on such trees must be non-overlapping, adjacent, and recursive, just as are the grouping and rhythmic hierarchies.

There is a marked correspondence between the hierarchical representation of musical events in time as postulated in *GTTM* and the hierarchical representation of relative syllabic stress in phonology (Liberman & Prince, 1977; Selkirk, 1980). Additionally, music and speech have comparable phrase lengths, and in both cases phrases are typically characterized by a pitch contour that rises and then falls over the course of the phrase. Although comparisons have often been made between music and language (e.g. Bernstein, 1976), only in these phonological aspects is the analogy well supported. The evidence and theory suggesting syntactic or semantic parallels in music and language are less compelling.

The Relationship between Time and Pitch

A final issue in musical timing is the degree of interaction between the pitch-based and rhythmic components of music. Some accounts have emphasized an independent and additive relationship between the two in determining musical expectation (Monahan & Carterette, 1985; Monahan et al., 1987; Palmer & Krumhansl, 1987a, 1987b; Smith & Cuddy, 1989; Bigand, 1997). Others have argued that there is a stronger dependence and interactive relationship between the two, as evidenced by judgments of melodic completion (Boltz, 1989a, 1989b), duration estimation (Boltz, 1989c, 1991b, 1993b; Jones & Boltz, 1989; Jones, Boltz, & Klein, 1993), recall (Boltz, 1991a; Boltz & Jones, 1986), and recognition (Jones et al., 1987; Boltz, 1993a; Jones & Ralston, 1991; Bigand & Pineau, 1996).

Boltz (1998) suggests that most musical sequences are highly coherent events, in that temporal and nontemporal structure are correlated and listeners encode these two dimensions together in memory. This is supported by the fact that participants can accurately give a duration judgment for a coherent musical sequence regardless of whether they attended to the duration or pitch alone or in combination. For incoherent sequences, accurate duration estimates can only be given when that dimension was attended (Boltz, 1992, 1998).

Jones (1987; Jones & Boltz, 1989) has proposed a theory of dynamic attending, in which different kinds of accent structures are attributed to both pitch and rhythmic organization in music. Accent coupling occurs in a melody when both melodic and temporal accents coincide. Such markers reorient attention and manipulating them can cause differences in the detection and recognition of musical targets (Jones et al., 1981, 1982).

MUSICAL PERFORMANCE AND ABILITY

Study of musical performance can yield insights into the mental representations used to interpret and plan the production of a piece and can provide additional clues to the kinds of information to which listeners attend when interpreting the performance. More generally, musical performance offers an opportunity to study complex motor behavior and the acquisition of cognitive skill. The reader is referred to additional reviews by Palmer (1997), Gabrielsson (1999), and Sloboda (1984, 1985, 1988).

Interpretation and Planning

The errors that musicians make are not random; mistakes often reflect the underlying representations of the music and the plan for executing the performance. We often think of pitch errors as being extremely salient, but Repp (1996b) has illustrated that the majority of errors made by trained pianists go undetected; errors vary along a continuum of perceptual salience. Conversely, trained pianists will automatically correct some errors in the score without realizing they are doing so, particularly when the error occurs in the middle of a phrase. This is a musical analogue of the proof-reader's error (Sloboda, 1976).

Palmer and colleagues have used production errors in piano performance as an index of the kinds of representations musicians use when planning, reflecting knowledge of diatonicity, melody, and harmony. The kind of musical knowledge emphasized in these errors will vary depending on the type of musical context, such as whether it is homophonic, having one primary melodic line, or polyphonic, having multiple melodic lines (Palmer & van de Sande, 1993). This kind of approach also supports the idea that performers break a piece of music into segments for the purposes of planning, ones that reflect the phrase structure of the piece (Palmer & van de Sande, 1995). The performer's representation of the local temporal organization of music has also been investigated by measuring errors in performance. Drake et al. (1991) found that pianists were more successful at reproducing melodies when different kinds of accent structures (metrical, melodic, and rhythmic) coincided and less successful when they conflicted. Furthermore, accent structures can affect the way in which the performer varies intensity, inter-onset timing, and articulation (Drake & Palmer, 1993).

Another cue to how performers process music is their eye movements when reading a score. Pianists' saccades reflect the relative harmonic or melodic content of the piece being played, with more vertical saccades for homophonic music, in which information at each time point can be chunked into one harmonic event, and series of horizontal saccades for polyphonic music, in which multiple melodic lines are occurring simultaneously (Weaver, 1943; Van Nuys & Weaver, 1943). The number of notes that performers can produce after the removal of the music they are reading, referred to as the *eye-hand span*, is affected by the phrase structure in music. When the end of the phrase is just beyond the average length of an eye-hand span, the span is stretched up to a limit. Conversely, when the end of the phrase is before the average length of the span, the span is contracted (Sloboda, 1977; see Sloboda, 1984 for a review of music reading). Phrase lengths are constrained by capacity limits as well as structure, as evidenced by performance errors (Palmer & van de Sande, 1993).

Communication of Structure

A second major class of experiments in musical performance involves how musicians, through the nuances of the performance, communicate structure to the listener. The written notation of Western music represents pitch and duration much more explicitly than it does the structural and expressive principles, such as phrasing and tension-relaxation. However, the performer provides information about these unwritten aspects of the piece to the listener, often through systematic deviations from the notated music. In many cases the qualities that lead a listener to describe a performance as "musical" are changes in tempo, dynamics, and synchrony, done in a systematic way as to bring the structure of the piece across to the listener, as will be explained next. Investigations of this issue usually involve mastered performances by expert

musicians, unlike the previous body of research which requires errors (for review see Gabrielsson, 1999).

Performance expression can affect the listener's perception of rhythm, melody, and harmony. One piece of information that can be provided to the listener through deviations from the exact is the meter of the piece. For example, experienced musicians can tell the difference between two different recordings of the same piece, played by performers who read the piece with the barlines drawn in different phases (Sloboda, 1983). Performers also have a tendency to place the primary voice or melody slightly ahead of the other voices. This has been found both for ensembles (Rasch, 1988) and individual pianists (Palmer, 1989; Repp, 1996a; Goebl, in press). Different melodic intentions on the part of the performer result not only in different degrees of melodic lead, but also different melodic interpretations on the part of the listener (Palmer, 1996). Additionally, performance expression may enhance the listener's perception of key modulation (Thompson & Cuddy, 1997).

Musicians cannot help but play nuances; even when asked to play mechanically, expressive timing differences remain (Palmer, 1989; Drake & Palmer, 1993; Penel & Drake, 1998; Repp, 1999a, 1999c). Listeners prefer and expect certain kinds of tempo deviation, particularly a slowing of tempo at the ends of musical phrases. In an analysis of performances of a Schumann piano work, Repp (1992b) found that systematic deviations from an exact tempo occurred during a recurring melodic gesture. Musicians but not non-musicians prefer to hear this kind of temporal nuance when listening to synthesized musical performances (Repp, 1992a). Furthermore, evidence suggests that listeners expect to hear a slowing of tempo at the end of a musical phrase; a lengthening is more difficult for the listener to detect when it is placed at the end of a phrase relative to the middle (Repp, 1992c, 1998b, 1999b, see Figure 6). Converging evidence comes from the study of expressive imitation; pianists can imitate phrases with expressive timing deviations well only if the deviations are related to the structure of the music (Clarke, 1993; Clarke & Baker-Short, 1987; but see Repp, 2000). There may be a connection between such temporal elements in music and kinematics, as suggested by Truslit (1938; see Repp, 1993). Just as biologically-realistic variations in movement velocity are perceived as constant (see Viviani & Stucchi, 1992), music may appear to progress at a constant tempo when played with expressive timing deviations (Repp, 1998a; Friberg & Sundberg, 1999; Penel, 2000).
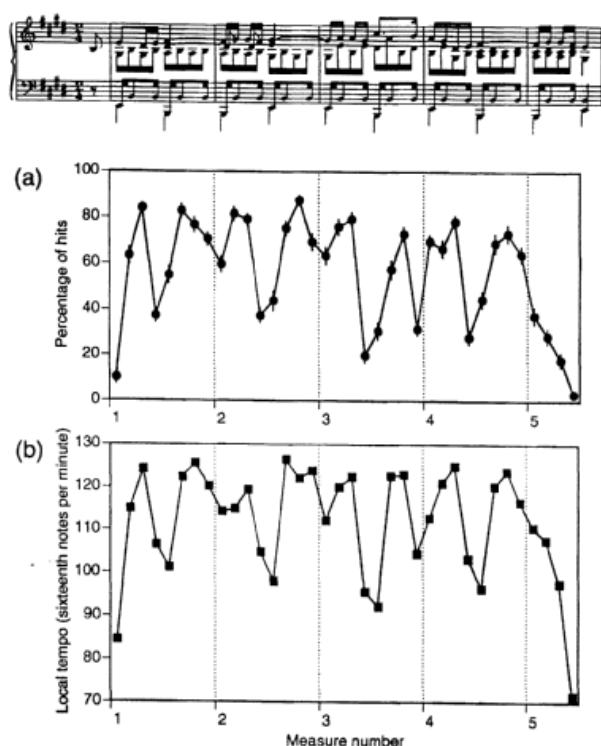
Figure 6: The representation of time in a musical context. Musical phrase structure warps the perception of time. The ability of a listener to detect an experimental lengthening (a) in a mechanical performance of Chopin's Etude in E Major (Op. 10, No. 3) is correlated with the points in time where musicians typically provide such lengthening (b). From Repp (1999b). *Copyright ©1999 by the Psychonomic Society. Reprinted with permission.*

Musical Expertise and Skill Acquisition

There is also a growing body of research on the acquisition of skills involved in the performance of music, specifically piano performance. Children with more musical training plan their movements earlier, are quicker to detect and correct their errors, and are able to move past mistakes (Palmer & Drake, 1997). In addition, musical training as well as practice with a particular piece are associated with improvements in tempo, pitch accuracy, and relative timing of events (Drake & Palmer, 2000). Furthermore, the mental representations of motor events in musical performance may become more conceptual and less tied to motor representations for advanced musicians, as suggested by a transfer of learning study done by Palmer and Meyer (2000). Sloboda et al. (1998) conducted a study of fingering accuracy in Czerny piano exercises and suggest that expert pianists have overlearned rule-governed response sequences that are triggered by familiar patterns in a score.

Differences also exist between musicians with different kinds of performance experience. Pianists whose primary emphasis is solo performance do worse than accompanists in sight-reading, but show greater improvements with repeated practice (Lehmann & Ericsson, 1993). Proficient sight-readers also plan farther ahead; Sloboda (1977) found that when reading melodies good instrumentalists had eye-hand spans of up to seven notes.

A related set of issues are the environmental factors that are associated with (and perhaps causally related to) the development of musical skill. Not surprisingly, one major predictor of musical skill is the amount of formal practice undertaken (Ericsson et al., 1993; Sloboda et al., 1996). Additionally, children who are successful in their private instrumental lessons tend to have parents who are highly involved in their children's early stages of learning and who also listen to (but not necessarily perform) music themselves (Davidson et al., 1996). One study of students' impressions of their music teachers revealed that effective initial teachers are perceived by their pupils as having positive personal characteristics (such as friendliness), but at later stages of learning, performance and professional skills are weighted more heavily (Davidson et al., 1998). Other studies have addressed the effects of sibling role models and peer opinions on the progress of musical training in children (for review see Davidson et al., 1997). Links between musical development and personality (Kemp, 1997) and gender (O'Neill, 1997) have also been suggested. Although notions of individual differences in musical development often are based on the concept of innate talent, not all music psychologists agree with this interpretation (see Sloboda et al., 1994; Howe et al., 1998, with commentaries).

THE COGNITIVE NEUROSCIENCE OF MUSIC

Having reviewed the literature to this point from the perspective of cognitive psychology, we must now ask how the mental algorithms related to music cognition are implemented in the brain. Initially such investigations focused on the perception of pitch. More recently, the kinds of processing explored in these studies have expanded to other levels of musical organization. Three general categories of approach have emerged: neuropsychological studies involving patients with damaged or resected brain regions of interest, neuroimaging studies concerned with patterns of metabolism and blood flow, and electroencephalography or the measurement of small electrical potentials on the surface of the head. Peretz (1993, 2001) has provided reviews of the first area, and Besson (1997) has provided a review of the third.

Neuropsychology

The animal literature provided one of the first clues regarding the processing of pitch in the brain. Research on cats lends support to the idea that the auditory cortex is required for a unified pitch percept, including the extraction of the missing fundamental, but not simple frequency discriminations, which may be computed subcortically (but see Johnsrude et al., 2000). Heffner and Whitfield (1976) trained cats in a conditioned avoidance paradigm using complex tones as stimuli. First the cats were trained to avoid a shock by ceasing to lick a cup when a rising tone pair was played. Falling pairs were not associated with the shock and thus were ignored by the cats. After this training, pairs of harmonic complexes were presented such that when the component frequencies were rising in pitch, the implied fundamental frequency was falling, and vice versa. The cats continued their avoidance behavior as if they were processing the stimuli according to the implied fundamental frequency of the tone complexes. In a later study, Whitfield (1980) demonstrated that cats trained in such a manner who then received ablations of auditory cortex could be retrained to make responses to individual frequencies of complex tones (the spectral pitches), but not to the pitch implied by the group of frequencies as a whole (the virtual pitch).

Adapting this paradigm to humans, Zatorre (1988) found that an intact right primary auditory cortex, located in Heschl's gyrus, was needed to extract virtual pitch from harmonic complexes with missing fundamental frequencies. Patients who had undergone temporal lobe excisions that included the right Heschl's gyrus were impaired in pitch extraction, whereas patients with complementary lesions on the left side or more anterior regions in the temporal lobe were not impaired. These results suggested that the right primary auditory cortex and perhaps more posterior secondary auditory cortices are necessary for pitch processing.

A preferred role for right temporal cortex as well as the right frontal cortex in the processing of pitch was also suggested by a study involving a short-term pitch retention task (Zatorre & Samson, 1991). Individuals with unilateral temporal and/or frontal excisions were asked to perform two pitch tasks. None of the patients were impaired on the control task, which was a comparison of two pitches over a delay. However, when the delay contained distracter pitches, all of the groups of right-hemisphere (and not left-hemisphere) patients were impaired relative to controls.

Pitch extraction therefore does seem to rely more heavily on right than on left hemisphere mechanisms. The picture is more complex, however, for the perception and cognition of pitch sequences or melodies. Early studies suggested a predominant role for the right auditory cortex for melodic processing (e.g. Shankweiler, 1966; Schulhoff & Goodglass, 1969), with the role of the left hemisphere limited to the more verbal aspects of music such as the lyrics (e.g. Gardener et al., 1977; for review see Zatorre, 1984). However, a frequently-cited psychological study by Bever and Chiarello (1974) showed that musicians and non-musicians have different hemispheric asymmetries, left and right respectively, as suggested by corresponding contralateral ear advantages for melodic perception. Peretz and Morais (1980) suggested that these differences are due to a global versus local processing difference for melodies in the right and left hemispheres, respectively. Non-musicians also recruit the left hemisphere more significantly when they process in a more analytic manner, as evidenced by an increasing right-ear advantage.

This global-local distinction between the right and left hemispheres for melodic perception was also supported by Peretz (1990) in a neuropsychological study. Left-hemisphere damage was associated with a failure to use local information (intervals) and right-hemisphere damage as associated with a failure to use either global (contour) or local information, recalling the distinction between scale and contour proposed by Dowling (1978). This is consistent with at least two interpretations: one in which local processing occurs bilaterally or one in which it occurs in the left hemisphere but is dependent upon prior global processing in the right. The former interpretation is supported by Liégeois-Chauvel et al. (1998), who in a study of sixty-five unilateral temporal cortectomy patients found a functional asymmetry in contour and interval processing. Their data support a role for bilateral posterior temporal gyrus in interval processing and a role for the right posterior temporal gyrus in contour processing.

The temporal dimension of music has been less systematically investigated than pitch. In addition to the hemispheric asymmetry in melodic perception, Peretz (1990) also found that damage to either hemisphere resulted in an impairment in rhythm but not meter perception (see also Shapiro et al., 1981), which supports the distinctness of these musical constructs as well as a possible primacy for metrical over rhythmic perception, as Lerdahl and Jackendoff's (1983)

GTTM would suggest. Liégeois-Chauvel et al. (1998) also found that the anterior portion of the temporal lobe, bilaterally, was essential for determining meter. The double dissociation between pitch and rhythmic ability in these two studies suggests that these two components of music are anatomically separable to some degree (see Figure 7).
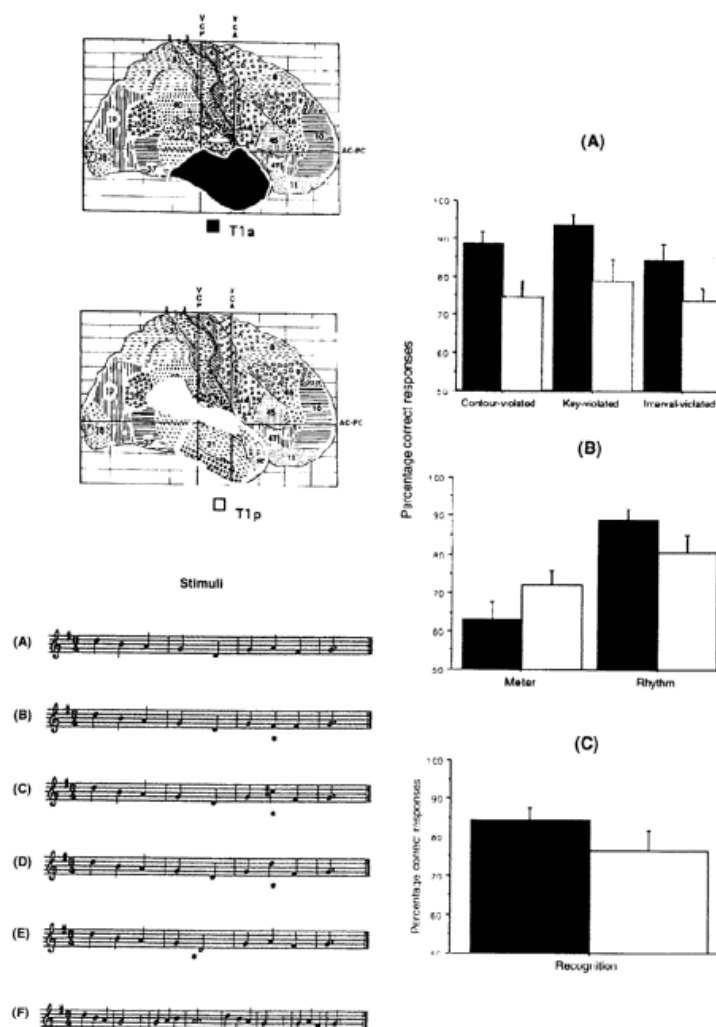

Figure 7: The superior temporal plane in musical processing. Discrimination and recognition of melodies and rhythmic patterns are impaired more following excision of the posterior part of the superior temporal plane (T1p, white bars) than more anterior regions of the temporal lobe (T1a, black bars). The pattern reverses for a metrical discrimination between duple meter (marches) and triple meter (waltzes). For the discrimination task, stimuli were presented in pairs (F) of the initial melody (A) and one of the following: (B) contour change, (C) key violation, (D) interval change with contour preserved, or (E) rhythmic change. From Liégeois-Chauvel et al. (1998). *Copyright ©1998 by Oxford University Press. Reprinted with permission.*

Neuroimaging

The neuroimaging studies to date in the field of music cognition in many cases have shared similar motivations with the neuropsychological studies, addressing the location and lateralization of pitch and melodic processing. An additional approach of interest has been to identify the task-specific brain regions associated with high-level musical processing, including regions associated with musical short-term memory (Zatorre et al., 1994), musical imagery and music-related semantic retrieval (Zatorre et al., 1996; Halpern & Zatorre, 1999), and absolute pitch processing (Zatorre et al., 1998). We will discuss the last area more fully as an example.

Imaging studies of absolute pitch implicate a stronger role for the left hemisphere than does much of the previously discussed neuropsychological work on pitch. An anatomical magnetic resonance imaging (MRI) study has demonstrated a leftward anatomical asymmetry in musicians with absolute pitch in the planum temporale, the surface of the superior temporal gyrus posterior to Heschl's gyrus (Schlaug et al., 1995; but see Westbury et al., 1999). Left frontal regions may be involved as well. Using positron emission tomography (PET), Zatorre et al. (1998) examined musicians with absolute pitch (AP) and relative pitch (RP) on a pitch judgment task of relative pitch (major/minor third identification). In a passive listening condition, both groups showed activation to bilateral superior temporal gyrus, right inferior frontal cortex, and right occipital cortex. The left posterior dorsolateral frontal (DLF) region was highly activated in the AP possessors but not at all in the musicians with only RP. In the active task, additional activation for the AP participants was observed in areas including the *right* DLF cortex, but the previous activity in right inferior frontal cortex disappeared, and for the RP participants, the previously inactive left posterior DLF region was recruited. The authors interpret the automatic activation of left DLF cortex in the AP participants as the association between the pitches and their verbal labels. (The same area is activated in the active condition for both groups as the verbal label for the interval is being retrieved.) The authors also speculate that the lack of right inferior frontal activation during the active condition for AP listeners reflects the fact that they need not rely on their auditory working memory system to label the interval; they can use each note's verbal label to make that judgment.

Electroencephalography

Event-related potential (ERP) research has a strong advantage over brain imaging in temporal resolution, and the musical issues explored with this methodology, including pattern recognition, expectancy violation, and structural integration, reflect the exploitation of this advantage. Electrophysiological support for the harmonic hierarchy of stability was provided by Janata (1995), who showed that the P300 component was sensitive to the degree of harmonic expectancy. Comparing the processing of sentences and musical sequences that varied in syntactic congruity, Patel et al. (1998) found that the P600 components for language and music were indistinguishable and associated in both cases with increasing difficulty of syntactic integration. Patel (1998) suggests that although music and language have distinct syntax, the integrative mechanisms may overlap. This study found a music-specific component, the RATN (right antero-temporal negativity) in the 300-400 ms range, which may be the right hemisphere analogue to another language ERP, the LAN (left anterior negativity). The ERP responses to *semantic* violations in language (e.g. the N400) seem to be distinct from those to pitch violations (Besson & Macar, 1987; Besson et al., 1998). The ERPs related to harmonic processing are also distinct from those related to the perception of sensory consonance (Regnault et al., 2001).

Several ERP studies have also investigated the differences in auditory and musical processing between musicians and non-musicians. Tervaniemi et al. (1997) found that the mismatch negativity (MMN), a measure of preattentive auditory cortex change detection, was greater in musical participants compared to less musical participants when exposed to repetitive tone sequences containing infrequent order changes (but not pitch changes), even when the task was to ignore the sounds and read a self-selected book. Koelsch et al. (2000) found that non-musician participants display two characteristic ERPs when listening to chord sequences containing unexpected notes, furnished by Neapolitan chords in one experiment and tone clusters in another. The first was an early right-hemispheric anterior negativity (ERAN, a.k.a. RATN), which the authors interpret as the violation of culturally-determined sound expectancy, and a late bilateral-frontal negativity (P5) believed to reflect the integration of the unexpected chords into the previous context. Although these kinds of effects are similar for musicians and non-musicians, musical expertise and familiarity with a musical passage are associated with larger amplitudes and shorter latencies of the ERP response to pitch-based and rhythmic violations (Besson & Faïta, 1995).

The picture of how music is implemented in the brain has changed over the past twenty years. Rather than being viewed as a highly lateralized right-hemisphere counterpart of language, it is coming to be regarded as a set of different cognitive abilities, many of which are located in both hemispheres but have subtle laterality differences depending upon the particular computation at hand. The study of the biology of music has suggested both that the brain contains regions that may be developmentally specified for particular tasks (such as pitch computation within right posterior superior temporal cortex), and also that the brain combines distinct mechanisms and domains (such as, perhaps, pitch and temporal organization) to create emergent forms of cognition. Additionally, music allows us to observe how enculturation can affect the development of the physical structure of the brain.

MUSICAL UNIVERSALS AND ORIGINS

In the final section we examine the issues related to the origins of musical knowledge, both developmentally through the lifetime of the individual and historically through the existence of our species. One reason why music cognition is a good domain for the study of cognition more generally is that music is mediated both by innate knowledge, which is universal across all humans and is part of our evolutionary history as a species, and by learned knowledge, which can vary across cultures and is a product of cultural evolution. Note that this is different than the issue of individual differences and talents (Sloboda et al., 1994; Howe et al., 1998). Rather than considering the genetic and environmental sources of variability between individuals, we address the evolutionary and cultural sources of the knowledge that is common to the members of a given community. We focus on knowledge of pitch relationships, reflecting the field's emphasis in this area.

Developmental Music Cognition

One important aspect of music cognition that seems to be universal and is present in infancy is the perceptual fusion of harmonic spectra into pitches. Infants as young as seven months can categorize harmonic complexes based on pitch, including those with a missing fundamental. Clarkson and Clifton (1985) first trained babies to respond with a head turn to a change in pitch, which could be accomplished by attending to the fundamental frequency and/or the spectral envelope of a harmonic complex. When the infants met a criterion on this task they proceeded to a perceptual constancy trial in which they had to ignore changing frequency spectra that did not contain the implied fundamental frequency. The processing of pitch by seven-month-olds is very similar to that of adults in that pitch analysis is easier if the upper partials are greater in number (Clarkson et al., 1996), show a high degree of harmonicity (Clarkson & Clifton, 1995), and are not masked by noise (Montgomery & Clarkson, 1997). Infants do, however, require the harmonic spectra to consist of low, more easily resolvable frequencies than adults do (Clarkson & Rogers, 1995). Studying even younger infants, four-month-olds, Bundy et al. (1982) used a heart-rate habituation paradigm to demonstrate similar pitch processing even earlier in development.

Further, infants as young as three months display octave equivalence (Demany and Armand, 1984), suggesting the universality of the two dimensions of pitch discussed in the first section: pitch height and pitch class. Startle responses are observed when melodies are presented a second time with some of the original tones shifted a seventh or ninth, but not an octave (so long as the melodic contour is not disrupted). Not only does the octave have preferred status in music but so does the perfect fifth and other intervals with simple ratios (Trainor & Trehub, 1993a, 1993b; Schellenberg & Trehub, 1996a, 1996b; Trainor, 1997; Trainor & Heinmiller, 1998). Although universal, knowledge about pitch class and the special nature of certain intervals may not require special innate representations but rather may be a result of the passive internalization of harmonic regularities in the auditory environment (Terhardt, 1974; Bharucha & Mencl, 1996). Still, such early effortless learning may reflect innate biases that favor the octave, perfect fifth, and other intervals with simple frequency ratios as natural prototypes (Rosch, 1975b), being relatively easy to learn and represent.

Melodic contour is also a salient musical property in infancy, and its importance in musical representation may also qualify as a universal. Using a head-turning paradigm, Trehub and colleagues have shown that infants categorize transposed melodies (same intervals and contour) as the same, changed-interval melodies (with the same contour) as the same, but discriminate between changed-contour melodies (Trehub et al., 1984, 1985, 1987; see also Ferland & Mendelson, 1989). This use of contour as a way to represent melodies remains in late childhood, even though children improve in their ability to detect interval changes (Morrongiello et al., 1985). Such studies have also demonstrated an asymmetry in discrimination not unlike that found by Bharucha and Pryor (1986) for rhythm; interval changes are easier for children to discriminate when the more consonant variant is presented first (Schellenberg & Trehub, 1996a).

Not all elements of music appear with such precocity, however. The importance of the seven diatonic tones within a tonal context is something that Western listeners appear to have to learn. Infants at eight months of age discriminate when a melody is changed within the same key (diatonic change) as well as they do when it is changed outside of the key (nondiatonic change),

while adults do much better at the latter and actually worse than infants on the former (Trainor & Trehub, 1992). This contrasts with the fact that infants of the same age can discriminate between melodies based on Western scales but not melodies based on non-diatonic scales or scales with intervals smaller than semitones (Trehub et al., 1990), as well as between melodies based on major triads and augmented triads (Cohen et al., 1987). The ability to represent melodies within Western diatonic contexts does appear by school age; four- to six-year-old children are better at detecting a change of tone within a diatonic context than within a nondiatonic context, while infants are not affected by this manipulation (Trehub et al., 1986).

The importance of particular tones within the diatonic scale as cognitive reference points may emerge even later during the school-age period. Krumhansl and Keil (1982) reported that while children at age six and seven give preferential ratings to diatonic tones at the end of melodies, it is not until eight or nine that the notes of the tonic triad are given preferential ratings to the other diatonic tones (but see Speer & Meeks, 1985; Cuddy & Badertscher, 1987). Trainor and Trehub (1994) strengthened this result by showing that five-year-olds can detect out-of-key melodic changes better than within-key melodic changes, and that seven-year-olds have the additional ability to detect out-of-harmony within-key melodic changes (Figure 8).
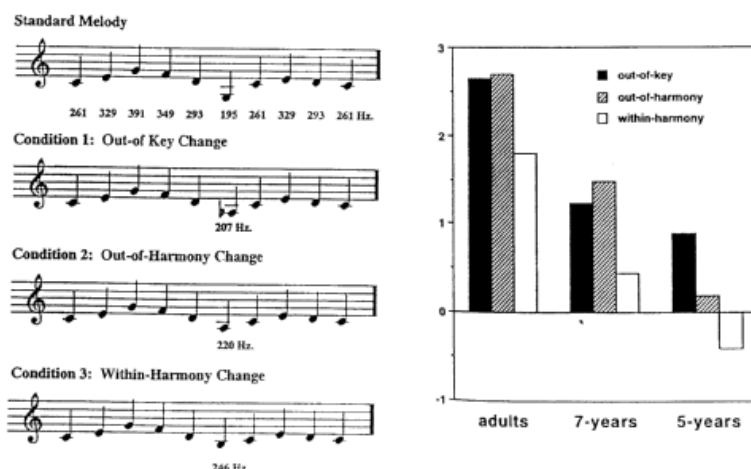

Figure 8: The development of tonal-harmonic knowledge in Western children. The ability to detect a changed note between a standard melody and three kinds of comparison melodies (left), as measured by d-prime scores (right), suggests that five-year-olds can represent notes in a melody in terms of key-membership (diatonic or non-diatonic) but that the ability to represent them in terms of the implied harmony within the key a does not emerge until age seven. In addition to these changes, adults also can detect changes that do not alter the harmony. They remain better at detecting out-of-harmony than within-harmony changes, however, suggesting that the representation of a melody is based on the implied harmonic structure. From Trainor and Trehub (1994). *Copyright ©1994 by the Psychonomic Society. Reprinted with permission.*

The developmental picture of music perception thus suggests that there may be universal core musical principles such as pitch perception and a preference for the octave and perfect fifth, and other culture-specific musical concepts that emerge only later in childhood such as specific scales and tonal hierarchies.

Cross-cultural Music Cognition

Many of the features of music perception that appear early in development are also found in the universal features of music across cultures. Dowling and Harwood (1986) suggest that several features are common to virtually all of the world's musical systems. These include (1) the octave as a basic principle in pitch organization, (2) a logarithmic pitch scale, (3) discrete pitch levels, (4) five to seven unequally spaced pitches in a scale, (5) hierarchies of stability for pitch, and (6) melodic contour as an important organizational device.

These universals may stem from basic features of the auditory cognition and/or basic features of human cognition more generally. We have discussed how octave equivalence may be innate or learned very early as a consequence of universal environmental features. A logarithmic pitch scale follows easily from the constraint of octave equivalence; if each successive frequency doubling results in a pitch of the same category, then changes in pitch within each octave must be logarithmic as well. Discrete pitch levels with five to seven pitches in each octave may be an example of the short term memory limitation for categories on a continuous dimension proposed by Miller (1956). The unequal levels of stability assigned to each of the notes of the scale have been suggested to be an example of Rosch's (1975a) cognitive reference points (Krumhansl, 1979), and the importance of melodic contour may stem from its similarity to prosodic patterns in speech (see Fernald, 1992).

The specifics of musical systems vary across cultures, and this kind of knowledge often is the kind that does not emerge until later childhood. One example concerns the specific sets of pitches chosen for the scales of a given culture. Western infants are equally good at detecting mistunings in their native major and minor scales and Indonesian scales (the pélog scale of Java), whereas Western adults show a strong advantage for the scales of their own culture (Lynch et al., 1990). Furthermore, estimations of interval sizes given by adults show an effect of the musical scale systems of the culture (Perlman & Krumhansl, 1996). The differences in perception of the native and non-native scales are apparent by late childhood even in non-musicians, although these differences are accelerated in children with formal musical training (Lynch & Eilers, 1991). Adult musicians and non-musicians may show the opposite trend, suggesting that skills learned in musical training eventually can be applied to music of other cultures (Lynch et al., 1991).

The specific tonal hierarchies of stability also vary across cultures. Using the probe tone technique with Western and Indian participants listening to North Indian *rags*, Castellano et al. (1984) found that although the structure in the melodies themselves influenced the responses of both Western and Indian listeners, tacit knowledge of the underlying scales significantly influenced the responses of only the Indian listeners. This tacit knowledge was presumably from prior exposure to pieces of music based on the same scales. Similar effects of enculturation on music cognition were found in a comparison between Western and Balinese listeners for their respective musical systems (Kessler et al., 1984). Recently, studies using two distinct musical

styles of Scandinavia have combined cross-cultural approaches with statistical and computational modeling (Krumhansl et al., 1999; Krumhansl et al., 2000; Krumhansl, 2000b).

Evolutionary Psychology of Music

A final topic in music cognition is how the relevant neural structure was shaped by natural selection throughout the evolution of our species (e.g. Wallin et al., 2000). Many authors have examined the possible selection pressures for musical behaviors themselves as an explanation for how music evolved in our species (e.g. Dowling & Harwood, 1982; Huron, 1999; Brown, 2000; Miller, 2000). Generally, these arguments center on the premise that music provided a reproductive advantage for the individual in the context of the social group or via mechanisms of sexual selection, as originally suggested by Darwin (1871). These approaches reflect a more general trend in psychology to regard cognitive abilities as specific adaptive solutions to evolutionary problems (see Tooby & Cosmides, 1992).

This kind of approach to the evolutionary psychology of music has been criticized by Justus and Hutsler (2000, under review), who have pointed out two critical issues that have been ignored in recent treatments of music evolution. The first is that much of what we regard as music is a product of cultural evolution or memetic transmission (Mead, 1964; Dawkins, 1976; Blackmore, 2000), as cross-cultural differences suggest. For these non-universal features of music it is not necessary to explain their adaptive utility from an evolutionary perspective; the evolutionary selection pressure in this case was for more general learning, linguistic, and mimetic abilities, while the musical knowledge was culturally selected. Second, many of the innate capacities that humans apply to music perception and music making may not have evolved as musical processes per se, but rather are processing mechanisms and knowledge selected for their utility within other domains such as auditory perception, conceptual representation, language, timing, and emotion. The latter idea is similar to the concept of exaptation, which Gould and colleagues have used to describe morphological forms that arise not because of direct selection pressures, but rather are the inevitable result of selection pressures for other attributes (Gould & Lewontin, 1979; Gould & Vrba, 1982; for a general application to cognition see Lewontin, 1990; for counter-arguments in the domain of language see Pinker & Bloom, 1990).

An examination of the developmental psychology of music, along with cross-cultural and evolutionary approaches, suggests that music is a reflection of both innate, universal cognitive mechanisms as well as cultural processes. Future integration of these three approaches may lead to answers to the most important questions of how and why our species came to be musical.

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