Rhythm and Pitch in Music Cognition

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Rhythm and pitch are the 2 primary dimensions of music. They are interesting psychologically because simple, well-defined units combine to form highly complex and varied patterns. This article brings together the major developments in research on how these dimensions are perceived and remembered, beginning with psychophysical results on time and pitch perception. Progressively larger units are considered, moving from basic psychological categories of temporal and frequency ratios, to pulse and scale, to metrical and tonal hierarchies, to the formation of musical rhythms and melodies, and finally to the cognitive representation of large-scale musical form. Interactions between the dimensions are considered, and major theoretical proposals are described. The article identifies various links between musical structure and perceptual and cognitive processes, suggesting psychological influences on how sounds are patterned in music.

Music perception has a long and distinguished history as a topic of psychological investigation. It has been considered within virtually every major theoretical framework of psychology and studied with diverse methodologies. Insights about music perception have come from approaches as wideranging as psychophysics, Gestalt psychology, information processing and cognition, the psychology of emotions, and neuroscience. Psychological interest in music has intensified significantly in the last few decades, as has interest in music by other disciplines such as computer science, linguistics, sociology, biology, and philosophy. At the same time, the specialties traditionally concerned with music—musicology, music theory, ethnomusicology, and music education—have shown an increased concern with understanding the psychological processes underlying musical behaviors. The motivation for this article is to summarize the currently available psychological literature on two well-developed areas of music perception and cognition research. It focuses specifically on musical rhythm and pitch, which are the primary dimensions of most musical styles. These are interesting psychologically because highly complex and varied patterns are formed from simple, well-defined units.

The major impetus for recent psychological research on music is cognitive psychology, which emphasizes the influence of knowledge on perception. According to this approach, a presented stimulus is interpreted by knowledge, sometimes called schemas, acquired through prior experience. In music, the schemas include, for example, typical rhythmic and pitch patterns. Perceptual information is assimilated to these, facilitating the organization of the sounded events into patterns and generating expectations for future events. Cognitive processing can also lead to systematic distortions so that the events may not be encoded and remembered exactly. Inherent constraints, such as short-term memory limits and biases

toward simple patterns, are also presumed to play a role. The knowledge that is invoked during listening depends on the larger context, encouraging the study of more musically realistic stimulus materials.

The emphasis on cognition also encourages the study of how musical knowledge is acquired. This topic is beyond the present scope, but it is important to note that three different approaches to this question are available in the context of music. The first is the developmental approach, and a growing body of research on this topic is uncovering an early predisposition for music processing in infants and children. The second approach is to look at effects of musical training. In this connection, two types of training should be distinguished: (a) instruction on instrument or voice and (b) academic training in music theory, analysis, composition, and history. Psychological studies on musical questions tend to use amateur musicians whose knowledge is derived primarily from learning to play music rather than from extensive academic study. The third approach is to vary familiarity with the musical style. This can be done, for example, by using contemporary art music or music from other cultures and/or comparing the results for subjects with different cultural backgrounds. Such comparisons are important for testing the generality of results, but most investigations take Western art music of the last few centuries (tonal-harmonic music) as the musical point of reference, as is done here.

This article consists of two sections, one on rhythm and the other on pitch. They follow the same organization in order to highlight parallels between these topics. Each section progresses from psychophysical results to high-level cognitive processes. The elements of rhythm and pitch each fall on a single underlying physical dimension—duration in the case of rhythm and frequency of vibration in the case of pitch. Each section begins with psychological results on basic perceptual capacities and limitations. These results typically come from experiments using brief, abstract stimulus materials. Listeners are highly sensitive to small differences on these dimensions. That is, they can discriminate reliably small differences in duration and pitch. The values used in music are considerably larger than the discrimination thresholds and can be related to an underlying grid. For rhythm, this grid is the regular periodic pulse of the meter. For melody and harmony, it is the

tones of the scale. Both rhythm and pitch structures use subdivisions of the dimensions that can be expressed as simple ratios of duration and frequency. Experimental studies show that listeners assimilate time and pitch to these musical categories. These ratios have a psychological basis that is reflected in musical notation, but musical performances deviate systematically from the simple ratios. Accent, meter, tone, and harmony are perceived hierarchically. Listeners encode and remember sequences of durations and pitches as whole patterns, with subpatterns embedded within larger patterns. Each section concludes with a summary of interactions between rhythm and pitch and their characterization as high-level cognitive representations. The large literature precludes an exhaustive survey. This selective review focuses on representative studies and methodologies.[1]

Rhythm

Basic Psychological Research on Rhythm

Introduction. Basic psychological research on rhythm is directed at describing human capacities for processing temporal information. Experimental research typically uses patterns constructed of tones of varying durations or very brief tones at varying delays. Usually, the pitch of the tones is not simultaneously varied. The time measurement of most interest is the time between the onsets of successive events, called the inter-onset interval (IOI). This is of particular interest because the time between events, rather than their duration, primarily determines the perceived rhythm. Psychological research on rhythm measures time in milliseconds rather than beats per minute (bpm). Some reference conversions may, therefore, be useful: Sixty bpm is equal to 1,000 ms; 120 bpm is equal to 500 ms; 240 bpm is equal to 250 ms. Research on rhythm tends to focus on durations in the range from 100 ms (1/10 of a second) to 5 seconds because this is the range in which temporal events are perceived as organized rhythms.

Time perception. If the time between events (such as brief tones) is too short (less than 100 ms), listeners hear the sequence as a single, continuous event. If intervals between events are much greater than 1.5 s (1500 ms), listeners have difficulty grouping the sounds, which seem disconnected from one another (Fraisse, 1978). Larger, hierarchically organized rhythmic patterns consisting of groups of groups can be formed out to approximately 5 s. Fraisse relates this limit to the concept of the psychological present, defined as the interval of time during which events can be perceived without reference to memory. This is in the range of the length of auditory sensory memory, or echoic store. Estimates of the length of this store range between about 2 and 5 s (see, e.g., Darwin, Turvey, & Crowder, 1972; Treisman, 1964). Thus, perceptual organization of temporal patterns is possible only in a restricted range of times. That this range corresponds with the duration of rhythmic patterns typically found in music suggests a psychological constraint on temporal patterning in music.

Although time between events is most relevant to musical rhythms, brief mention should be made of psychological research on time perception. Listeners are sensitive to small time differences. With no context, a difference of about 8% is perceived (Kristofferson, 1980). Numerous studies have investigated the subjective duration of temporal events (Eisler, 1976). In these experiments, participants gave an absolute estimate of the dura-

tion. These judgments deviated from objective durations. Very short intervals tended to be overestimated, and large intervals tended to be underestimated. The point of subjective equality, where subjective judgments corresponded to the objective duration, was approximately 600 ms. In the range from 40 to 600 ms, the subjective duration of a time interval is proportional to the physical duration plus a constant of approximately 80 ms, called the *supplement* (Nakajima, 1987). The supplement may account for some discrepancies between notated rhythms and performed rhythms. According to this view, the performed values compensate for the perceptual supplement. However, other results are inconsistent with this view (Sternberg, Knoll, & Zukofsky, 1982). Sternberg, Knoll, and Zukofsky's (1982) study showed that short intervals were too long in both perception and production tasks. This is contrary to the perceptual feedback hypothesis, according to which subjective durations caused participants to adjust the performed durations. Methodological differences may account for the inconsistent results between these studies.

Periodic pulse. Fraisse (1956, 1963, 1978, 1982) has undertaken the most coherent and sustained program of research on the psychology of time. The following brief summary follows the review provided by Fraisse (1982), which contains an extensive bibliography. One component emphasized in this research is the fundamental role of a basic periodic pulse in both perception and physical activity. Many activities, such as sucking in newborn infants, rocking, walking, and beating of the heart, occur with periods of approximately 500 ms to 1 s. Spontaneous tempo, which is measured by the natural speed of tapping, tends to fall in the range from 380 to 880 ms, with 600 ms being a typical value. For some individuals, the values are as low as 200 ms, for others, as large as 1,400 ms. These individual differences are stable over time. For a given individual, spontaneous tempo of the forefinger correlates with movement of the palm of the hand, the leg, and the arm. Another experimental measure producing similar rates is preferred tempo. In this method, participants are asked to adjust the rate of sounds so as to appear most natural. These measures also center around 600 ms. The convergence of these different measures suggests the existence of a pacemaker or timekeeper that regulates the various activities.

People easily synchronize their movements with a regular sequence of sounds (Fraisse, 1982), which demonstrates a strong psychological link between rhythm perception and production. According to Fraisse, this ability appears early in life and appears quite naturally. Adults have difficulty breaking the synchrony, finding it easier to tap on the beat than after it. It should be noted that this ability to synchronize with the presented stimulus contrasts with most reactions that occur after the stimulus. This suggests that humans are able to anticipate a rhythmic stimulus and

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[1] Additional reviews can be found in books by Sloboda (1985), Dowling and Harwood (1986), Handel (1989), Krumhansl (1990a), and volumes of papers edited by Deutsch (1982, 1999), Howell, Cross, and West (1985), Sloboda (1988), Howell, West, and Cross (1991), Sundberg, Nord, and Carlson (1991), Jones and Holleran (1992), McAdams and Bigand (1993), Aiello and Sloboda (1994), Deliège and Sloboda (1996), Leman (1997), and P. Cook (1999). Specialized journals publishing articles on music perception and cognition include *Music Perception, Psychology of Music, Psychomusicology, Journal of New Music Research, Musicae Scientiae,* and *Systematische Musikwissenschaft (Systematic Musicology).*

send motor commands so as to coordinate movements precisely with it. It is notable that the range of accurate synchronization (approximately 150 ms to 1,600 ms) roughly corresponds with the range of durations in the other psychological measures just summarized.

Grouping. When listeners hear a sequence of identical sounds, they tend to group them by twos, fours, or less often by threes (Fraisse, 1982). Nothing objectively specifies the grouping, so it is called *subjective rhythmization.* The number of elements in the group depends on tempo; groups with more elements are formed at faster tempos. This tempo effect is also found in production. For example, when asked to produce groups of threes, listeners produce taps with an IOI of 420 ms on average; when asked to produce groups of fours, the rate was faster, with an average IOI of 370 ms. IOI and group size do not perfectly compensate for each other. For example, a group of four is only 1.8 times as long as a group of two, and a group of six is only 2.2 times as long. Similar effects are found in memory; more elements are correctly reproduced from memory if their rate is faster.

Objective rhythmization refers to the case when a difference is introduced into the sequence of sounds (Fraisse, 1982). For example, one element may be longer, louder, a different pitch, or followed by a longer pause. Experiments on how such sequences are grouped typically repeat the pattern multiple times. Listeners judge pauses to strongly mark group endings. When instructed to tap out groups of three or four, participants produced pauses of about 600 to 700 ms at group ends. Longer pauses are produced for more complex patterns, with the pause at least as long as the longest duration within the pattern. Pauses longer than 1,800 ms are not produced, however, as this would destroy the perception of a succession of groups. Lengthening a sound can function similarly to a pause in determining the end of a group. Element duration and intensity trade off with one another. A sound that is lengthened is perceived as more intense, and a more intense sound is perceived as longer. Longer and more intense sounds are heard as accented, and these elements tend to define the beginning of subjective groups. Similarly, a higher pitched sound tends to define the beginning of the group.

Related research by Garner and colleagues (summarized in Garner, 1974) used sequences made up of two different sounds, denoted X and O. A pattern might be represented by XXXOXOOO where X, for example, represents a higher (or louder) tone than O. In a typical experiment, the sequence was repeated at a relatively fast rate (more than 2–4 elements per second) until the participant could reproduce it by tapping on two different keys. As the complexity of the pattern increased, participants listened to more repetitions before they began tapping. Once they began, however, the responses were highly accurate, supporting the idea that they learned the pattern as a whole rather than piecemeal. The beginning of the response pattern tended to coincide with the beginning of the longest run of similar elements. Sometimes, the longest run of similar elements occurred at the end of the response pattern, but it was rarely in the middle. The grouping essentially never broke up runs of similar elements.

Simple ratios of durations. Returning again to research summarized by Fraisse (1982), rhythmic patterns are far easier for participants to produce than are irregular sequences, again emphasizing the strong rhythmical nature of human behavior. Rhythmic sequences are characterized by durations that approximate a 1:1

ratio or a 1:2 ratio. In particular, rhythmic sequences tend to be composed of two kinds of IOIs: short times of 200–300 ms, and long times of 450–900 ms. Durations tend toward equality within each of these categories. Even when instructed to produce arrhythmic patterns, participants show a strong tendency to produce near-equal IOIs, that is, IOIs with ratios near 1. However, arrhythmic patterns also contain IOI ratios in the range from 1.2–1.6, as though a rupture is caused by the departure from the 1:1 and 1:2 ratios. These findings suggest a psychological limit of about two duration categories, most often related by a 1:2 ratio, in rhythmic patterns (see, however, Gabrielsson, 1988, who makes a case for as many as four duration categories).

Implications of basic research for rhythmic patterns in music. Two important generalizations emerge from basic research on the psychology of rhythm. First, although humans quite accurately estimate time and detect small differences in duration, the most impressive abilities are found in the perception and production of rhythms. Thus, patterns of durations, rather than absolute durations, are psychologically primary. Second, rhythm perception is strongly linked to rhythm production. Essentially all of the results coming from experiments on perception have parallels in experiments on production. This suggests a strong motoric component to the psychological representation of rhythm. A number of more specific findings should also be recalled. Substantial evidence suggests that rhythms are based around a periodicity in the range from approximately 300 ms to 900 ms. Perceptual grouping of events is determined by multiple factors, including pauses and changes in duration, pitch, or intensity. Groups of groups can be formed, but total pattern duration appears to be limited to approximately 5 s. Finally, complex rhythmic patterns tend to consist of durations that are near either a 1:1 ratio (isochrony) or a 1:2 ratio.

The research summarized to this point is only indirectly concerned with rhythms in music, and the stimuli and tasks are highly artificial. Fraisse (1982) stated "the stimuli used were far from musical, since these researches used only taps, identical sounds, or at best, two types of sounds of different duration, intensity, or pitch. Musical rules, however, do not escape the fundamental laws that we have demonstrated" (p. 170). In support of this, he observed that rhythmic patterns in musical compositions tend to have durations in the range from 2 to 5 s. Within a composition, a very large majority (more than 80% on average) of notated durations fall into two duration categories: a short duration and a long duration. Moreover, these durations tend to be in a 1:2 ratio or, less frequently, a 1:3 ratio. In addition, the longer of the two durations almost always falls in the range between 300 and 900 ms. This convergence encourages research with more musically relevant stimulus materials and tasks, to which I now turn.

Research on Musical Rhythm

Introduction. Research on rhythm, oriented toward musical issues, has developed rapidly in recent decades (see Clarke, 1999, for a review). One impetus for this came from technological innovations (see, e.g., Shaffer, 1981) that allowed keyboard performances to be analyzed in detail. The timing of keypresses could be recorded with millisecond accuracy, and key velocity (which correlates with dynamics) could also be measured precisely. This made it possible to study differences between notated durations (theoretically, ratios of small integers) and performed durations

(which often deviate from simple ratios), slowing of tempo during rubato, and other expressive timing variations. Highly replicable and consistent patterns were found in expert performances. These empirical data have wideranging implications for the psychological study of motor behavior, cognitive representation of rhythm, and music-theoretical treatments of musical structure. Reviews written by Palmer (1997) and Gabrielsson (1999) contain extensive bibliographies of performance research. The following discussion focuses on rhythm perception, but the strong connection with performance research should be borne in mind.

Categorical perception. To begin with simple patterns, psychological studies show these are categorized by simple ratios of duration. In particular, ratios near 1:2 tend to be assimilated toward that value. In one representative study, participants (some of whom were musically trained) tapped in synchrony with a presented auditory pattern (Povel, 1981). The pattern consisted of two durations presented in cyclic fashion. The durations formed ratios that ranged from .25 (1:4) to .8 (4:5). The participants listened to the pattern, and as soon as they felt ready, they imitated (continued) the pattern a number of times. Patterns that consisted of small ratios were imitated with a somewhat larger ratio (closer to .5); patterns that consisted of large ratios were imitated with a somewhat smaller ratio (closer to .5). The pattern that had a ratio of .5 (1:2) was imitated most accurately. No systematic differences between musicians and nonmusicians were found. Additional experiments showed that with more complex contexts, integer ratios of 1:3 and 1:4 could be imitated, but differences started to emerge between musically trained and untrained participants. Additional evidence that temporal patterns are distorted in memory toward simple rhythmic patterns is presented by Deutsch (1986b).

Small integer ratios function as perceptual categories (Clarke, 1987). In one experiment, music students listened to a series of short musical sequences (tones varying in pitch) in which the durations of the last two tones ranged from a 1:1 ratio to a 1:2 ratio. Participants were required to identify whether the critical tones were of the type 1:1 or 1:2. They were also required to discriminate between pairs of critical tones that differed slightly. These two tasks, the identification and discrimination tasks, were patterned after studies of categorical perception in speech (Studdert-Kennedy, Liberman, Harris, & Cooper, 1970). The identification data showed the pattern characteristic of categorical perception, with one response persisting up until a certain ratio, followed by a sudden transition to the other response. The discrimination data showed greatest accuracy at the boundary between the two rhythmic categories, consistent with categorical perception. These results were found in both triple and duple meter contexts, but the position of the boundary was shifted. Similar results were obtained with performed rhythms. Meter (3/4 vs. 6/8) and accent (strong–weak versus weak–strong) may also be perceived categorically (Windsor, 1993). Rhythm perception is also subject to more complex musical influences. In one study, listeners had more difficulty detecting slightly increased durations where lengthening would typically occur in an expressive performance of a Beethoven piano sonata (Repp, 1992).

Models of rhythmic organization. To account for perceptual assimilation to simple ratios of durations and other effects in rhythm perception, Povel (1984) developed a temporal grid model. The temporal grid consists of a sequence of isochronous intervals generated by an internal clock or pacemaker. The temporal grid is expected to correspond with the rate that a listener would tap to the sequence. Selecting the appropriate grid is based on two considerations. First, each interval in the sequence is a potential candidate for the time unit of the grid. Second, the selected unit is the one that allows for the most economical description. Briefly, the grid is more economical (a) the more elements in the sequence that can be mapped onto the grid, and (b) the fewer the points in the grid without corresponding elements in the sequence. An elaboration of the basic model allows for additional subdivisions of the grid unit. Povel and Essens (1985) developed the temporal grid model further to take accents into account. These accents arise from the grouping of elements. Accents occur on isolated elements, the first and last elements of a run, and the second of a pair of elements. The model searches for a pattern of periodicities in the accents and selects the temporal grid with the best fit. Consistent with the model, experiments showed that reproduction accuracy was greatest for patterns that more readily induced a temporal grid, and theoretical complexity was correlated with complexity judgments. The Povel and Essens model can be criticized on the basis that it requires the whole sequence to be coded before the analysis begins.

Another model that served to sharpen the issues surrounding rhythm perception is found in Lerdahl and Jackendoff's (1983) *A Generative Theory of Tonal Music.* This model applies concepts of formal linguistics to music. Essentially, the problem is to determine rules that specify well-formed musical sequences, as in a grammar. An important distinction is made between meter and grouping. The term meter refers to the regular alternation of accents with one or more weak beats in a periodic pattern (corresponding to the bar). This is formalized as metrical hierarchies in the model's metrical component; it specifies the relative stress of each position in the bar. In contrast, the term grouping refers to the organization of events into groups. These groups need not be periodic nor coincide with metrical structure. The grouping component of the model specifies principles according to which elements group together. The groups are organized into hierarchical levels, with smaller groups combining to form larger groups at higher levels. Rhythm is the product of complex interactions between these two components. A related distinction is that between formal and figural aspects of rhythm, which arises in studies of how children represent rhythms graphically (Bamberger, 1991). Theoretical treatments of rhythm by Cooper and Meyer (1960) and Yeston (1976) have also influenced psychological studies of rhythm.

Metrical hierarchies. Psychological tests support the claim that a hierarchy of stress, that is, a pattern of strong and weak beats, is perceived (Palmer & Krumhansl, 1987a, 1987b). The specific model tested was the metrical component of Lerdahl and Jackendoff's (1983) model, which corresponds with intuitions. For example, in quadruple meter, the first beat has the highest stress, followed by the third beat, followed by the second and fourth beats, followed by the half-beats, and so on. Excerpts from compositions by Bach and Mozart were interrupted at different points in time. Listeners judged the excerpts as to whether they were good, complete phrases. The judgments correlated with the metrical hierarchy predictions. Convergent evidence for metrical hierarchies comes from judgments of goodness of fit and memory errors (Palmer & Krumhansl, 1990). In one experiment, listeners heard a sequence of low-pitched tones, which they were asked to

assign to the first beat of measures of two, three, four, or six beats. After a number of repetitions, a high-pitched probe tone entered somewhere between the context tones. Listeners rated how well the probe tone fit with the imagined meter. The judgments of both musicians and nonmusicians contained a metrical hierarchy, although it was more sharply differentiated for musicians.

A second experiment (Palmer & Krumhansl, 1990) used a similar procedure in a memory task. One probe tone was sounded, followed after a delay by a second probe tone. Listeners had to remember the position of the first probe tone relative to the imagined meter and judge whether or not it was the same as the second. Probe tones occurring in metrically strong positions were more easily recognized and less frequently confused with probes in weaker temporal positions. Only musicians performed this task, as it proved too difficult for nonmusicians. The hierarchy was also found by analyzing compositions by Bach, Mozart, Brahms, and Shostakovich. The frequency with which note events occurred in each temporal location within bars of 2/4, 3/4, 4/4, and 6/8 meter matched the perceptual and theoretical hierarchies. Thus, frequency distributions of musical events within bars could provide a cue to meter in addition to cues of accent and duration. It should be noted that this description of metrical hierarchies does not extend to musical styles with polyrhythms (more than one meter in use simultaneously) or additive rhythms (groups of different numbers of pulses, e.g., 4 + 4 + 2 + 4).

Models of meter perception. Various models have been proposed for how a listener determines the meter of a piece of music. The model proposed by Longuet-Higgins and Lee (1982) assumes that metrical analysis begins as soon as the sequence of elements begins. The first duration (between the first and second tones) is used to predict the time of the third element. If confirmed, the model constructs an additional level in a binary tree. If disconfirmed, the basic temporal interval is stretched to the interval between the first and third events. If needed, the model adjusts the position of the strong beat of the meter by shifting it to relatively long elements. Subsequent experimental evidence suggested further refinements of the model (Lee, 1991). A related model assumes that the processing of rhythm proceeds within the limited time frame of a phrase and that meter perception requires only limited cognitive capacity (Johnson-Laird, 1991). This model was proposed as a basis for determining families of similar rhythms.

Parncutt (1994) also considered how listeners assign metrical interpretations to rhythms. His study is exemplary in the precise level at which psychological data are quantitatively modeled. His experiment presented cyclically repeating patterns beginning at randomly selected points in the cycle at different tempos. Listeners were asked to tap along with the underlying beat or pulse. Responses tended toward a moderate periodicity of approximately 600–700 ms. Perceptual salience was measured by the number of times a given pulse (specified by its period and phase) was selected by the listeners. These experimental measures were well fit by a model synthesizing a wide range of prior theoretical and empirical research. This model's central assumptions are: (a) The accent of an event increases with its duration up to an interval of 1 s, (b) the salience of a pulse depends on the number of events matching the hypothetical pulse, and (c) pulse sensations are most salient in the range around 600–700 ms. In a second experiment, listeners heard the same rhythmic patterns with one of the elements marked by an extra sound. The task for listeners was to judge whether the extra

sound fell on or off the beat, using a four-point rating scale of strength. Although the pulses were quite unambiguous, the pulse corresponding to the cycle length was difficult to judge. This can be accounted for by the fact that the cycle length exceeded the optimal 600–700 ms periodicity.

Finally, brief mention should be made of three related artificial intelligence models of meter perception. The connectionist model of Desain and Honing (1989), extended by Desain (1992), addresses the *quantization problem*—assigning metrical structure to sequences of events that may undergo expressive timing variations. The model takes the form of a network that acts as a shift-register, processing durations between both successive and nonsuccessive events. The durations are adjusted toward small integer ratios. The model is capable of extracting hierarchical metrical structure even though it lacks a symbolic representation of meter. Another subsymbolic model by Large and Kolen (1994; Large & Jones, 1999) is based on oscillator units. These can entrain (phase- and frequency-lock) to periodic components of rhythmic patterns. This model offers an alternative to models assuming an internal clock or pacemaker as described above and is informed by research on rhythmicity in motor performance. The implications for temporal expectation are stressed in both these proposals. Todd (1994) developed a filter-based model motivated by auditory physiology. The model assumes that temporal filters integrate energy on multiple time scales. Low-pass time-domain filters determine grouping and accent, and band-pass frequency-domain filters determine meter and tempo. The model produces a treelike "rhythmogram" showing the grouping and accent of temporal events.

Grouping and accent. Rather less attention has been directed at grouping and accent. Grouping events into segments is fundamentally important in music as well as in other psychological domains. Using a technique developed to study language processing, participants tended to mislocate clicks added to a melody in the direction of phrase boundaries (Sloboda & Gregory, 1980). This indicates the psychological coherence of phrases. Even infants are sensitive to phrase structure in music (Jusczyk & Krumhansl, 1993; Krumhansl & Jusczyk, 1990), just as they are to clause structure in language. Analysis of the music used in these studies suggested that longer durations and drops in pitch signal phrase endings—cues that also appear to operate in language. Segmentation can also result from changes in other attributes such as pitch register, timbre, dynamics, and articulation. Perceptual judgments reflect all these factors, generally supporting the principles formalized in the grouping component of the Lerdahl and Jackendoff (1983) model (Deliège, 1987). A number of investigators have studied segmentation of whole musical compositions (Clarke & Krumhansl, 1990; Deliège, 1989; Deliège & El Ahmadi, 1990; Imberty, 1981; Krumhansl, 1996). These range from classical to contemporary styles. The method asks listeners to make judgments of section ends in real time while listening to the music. Considerable consistency is found across listeners independent of their musical training and familiarity with the music, and a core set of factors appears common to the musical styles, including pauses, changes in pitch register and dynamics, and return to previously presented material.

No fixed relation holds between grouping and accent. Accent accrues to events of long duration and events followed by pauses, and these tend to occur at the end of segments. The first of a run

of identical elements, which tend to begin subjective groups, also appears accented. An element can be accented by dynamics independent of its position in the group. In addition, accents are induced by melody and harmony. Concerning melodic contour, the first of two intervals in opposite directions receives the strongest accent (Thomassen, 1982). This result stimulated a model assuming that acoustical factors exert an influence over a short time span. In the model, pitch contour changes are processed in a "window" that slides along the tone sequence determining accents by differences in magnitude and direction. In a study of harmonic accent, chord changes were more salient than temporal accents in determining perceived rhythm and the position of the downbeat (Dawe, Platt, & Racine, 1993). Thus, accent is determined by a variety of factors.

Rhythmic organization and pitch. Rhythmic organization can influence the perception of pitch in a variety of ways. For example, pitch changes are easier to detect in the context of a predictable temporal pattern, especially when they occur at points of strong metrical accent (Jones, Boltz, & Kidd, 1982). From this and related results, Jones and Boltz (1989) developed a temporally based theory of attending. They claimed that perception, attention, and memory are inherently rhythmical. Temporal regularities in the environment entrain processing resources, determining the nature and the quality of perceptual encoding. A similar proposal is found in the "expectancy windows" notion of Dowling, Lung, and Herrbold (1987; Dowling, 1990). Listeners rhythmically control attention, aiming expectancies toward regions of pitch and time that are likely to contain critical events. To study this, Dowling et al. used two interleaved melodies in which successive tones alternated back and forth between the two melodies. A melody was identified more accurately if its tones fell on rather than off the beat. In a related result, listeners could detect the presence or absence of a melody interleaved with another melody only when it was specified in advance (Dowling, 1973). This effect is accounted for by the idea that expectancy operates by selecting only those elements that match the cued target melody.

Rhythmic accent can also affect memory for melodies. Performance is enhanced when tones that are stable in the key (see the *Tonal hierarchies* section below) mark phrase endings but only when they are emphasized by temporal accents (Boltz, 1991a). Memory retention of pitch contour and information at phrase endings is affected similarly. Interactions between pitch and time also alter estimates of time (Boltz, 1991b, 1992, 1995). The judged duration of a sequence may be over- or underestimated depending on whether the melody is manipulated to direct attention to lower or higher order patterns. Musical sequences that were filled with regularly timed information and that ended predictably were judged most accurately. When a melody's structure was obscured by prolonging tones to conflict with phrase boundaries, time estimates were less accurate and more variable, and the durations were consistently overestimated. A related study presented subjects with harmonized melodies that ended on a chord that was strongly expected, moderately expected, or harmonically unexpected (Schmuckler & Boltz, 1994). The temporal structure of the accompanying chords and of the final chord was manipulated. These manipulations influenced both the judgment of whether the final chord fit with the sequence and the reaction time needed to make this judgment. These results suggest complex interactions between rhythm and pitch in perception and memory.

Dimension of the experience of rhythm. Finally, Gabrielsson (1973a, 1973b) investigated the qualities of rhythms in more global psychological terms. This program consisted of an extensive series of experiments on the experience of rhythm. The rhythms were monophonic rhythms played on piano or drum, polyphonic rhythms produced electronically, and real music. Included was a fairly comprehensive set of dance rhythms. Listeners gave adjective ratings and made similarity judgments of pairs of rhythms. Factor analysis and multidimensional scaling, which extract dimensions of perceptual difference, were applied to the data. The dimensions fell into three classes. The first class includes cognitive-structural dimensions, such as meter (whether duple, triple, and so on), accent on the first beat, clearness of accent, uniformity versus variation, and simplicity versus complexity. The second class includes movement-motion dimensions, including rapidity, rate of elements, forward motion, and such movement associations as dancing versus walking, rocking versus knocking, graceful versus thumping, and solemn versus swinging. The third class includes emotion dimensions such as vital versus dull, excited versus calm, rigid versus flexible, and solemn versus playful. Thus, rhythms appear to have effects on three psychological levels: cognitive, motoric, and affective.

Pitch

Basic Psychological Research on Pitch

Introduction. The source of any sound is a vibrating body that produces a sound pressure wave. For many sources, particularly musical instruments, the sound pressure wave is approximately periodic for short durations. That is, the pressure wave repeats over time. The fundamental frequency is the number of cycles of the wave form per second (hertz, [Hz]). Periodic tones are produced by vibrating bodies, such as strings on violins and pianos, and resonating columns of air in bassoons and organ pipes. All periodic tones (except sine waves) contain a number of frequency components, called harmonics. Their frequencies are integer multiples of the fundamental frequency. For example, an A440 has harmonics at 440 Hz, 880 Hz, 1,320 Hz, 1,760 Hz, and so on. Lower harmonics are generally louder than higher harmonics. Some instruments, such as snare drum and wood block, do not produce periodic wave forms and therefore do not give rise to a well-defined sense of pitch. The fundamental frequency (lowest harmonic) of musical instrument tones ranges from approximately 25 Hz to 4,000 Hz, although humans can hear frequencies up to 15,000 Hz or higher. Fundamental frequency is related to the psychological dimension called pitch. As frequency increases, the perceived pitch is said to get "higher."

Pitch perception. Basic studies on pitch show that even very short tones (on the order of 8–10 cycles; Robinson & Patterson, 1995) give rise to a pitch sensation. Essentially all musical tones are considerably longer than this value. Listeners are also very sensitive to small frequency differences. A difference of about 0.5% is perceived, with somewhat larger values for softer and lower tones (Weir, Jesteadt, & Green, 1977). Musical intervals are considerably larger than this value; a semitone is a frequency difference of approximately 6%. Fletcher and Munson (1933) showed that the amplitude needed for a tone to be heard (threshold) is lowest for tones in the range 2,000 to 5,000 Hz where the

threshold is approximately 0 decibels (dB, a measure of sound intensity). This threshold rises (less sensitivity) at the low end of the hearing range (to approximately 70 dB) and at the high end of the hearing range (to approximately 20 dB). Within most of the musical range, perceived pitch approximates a linear function of the logarithm of frequency. Equivalently, constant ratios of frequencies give rise to constant perceived pitch differences. (Perhaps it should be noted that Stevens and Volkmann, 1940, proposed the mel scale for nonmusical pitch, which is a function of both frequency and log frequency.)

Musical intervals. Of all physical dimensions, pitch is perhaps the most differentiated perceptually, the most elaborated cognitively, and the most heavily theorized (in both music and language). One distinctive aspect of musical pitch is the special status of intervals. For example, a perfect fifth is produced by any two tones with fundamental frequencies in the ratio 3:2. The two pitches can be shifted up or down the dimension of frequency and, as long as their ratio remains unchanged, they still produce the same musical interval. At the core of theorizing about pitch is the belief that numbers provide a suitable vehicle to move between the realms of physics, psychology, and music. This belief is often attributed to Pythagoras (ca. 570–500 B.C.) who associated harmonious sounding musical intervals with vibrating strings whose lengths form simple numerical ratios (e.g., 2:1, 3:2), although the essence of the theory may have been developed earlier by the Chinese.

The greatest single achievement in studies of pitch is Helmholtz's 1863 treatise *On the Sensations of Tone as a Physiological Basis for the Theory of Music* (1863/1954). The program of research set out there sought correspondences between physical acoustics of vibrating bodies, human auditory physiology and perception, and musical structures such as scales and harmonies. As described by Helmholtz, the tones used in Western music (and, to some extent, music of other cultures) bear a close relationship to the harmonics of complex tones. The first and second harmonics form an octave, the second and third harmonics form a perfect fifth, the third and fourth harmonics form a perfect fourth, the fifth and fourth harmonics form a major third, and the fifth and sixth harmonics form a minor third. The seventh harmonic does not form a musical interval, but the eighth and ninth harmonics form a major second. Musical intervals are also formed by nonadjacent

harmonics, such as the major sixth, which is formed by the third and fifth harmonics, and the minor sixth, which is formed by the fifth and eighth harmonics.

Consonance and dissonance. The perceptual dimension of consonance versus dissonance is related to ratios of frequencies. In experimental tasks eliciting consonance judgments, the instructions variously described consonant intervals as pleasant, smooth, pure, and giving a sense of fusion or unity (see Malmberg, 1918, for a summary of early studies; Krumhansl, 1990a, for more recent studies). Despite the variety of adjectives used, intervals are ordered quite consistently. The unison (1:1) and octave (2:1) are the most consonant, followed by the perfect intervals, the perfect fifth (3:2) and the perfect fourth (4:3). The major third (5:4), minor third (6:5), major sixth (5:3), and minor sixth (8:5) are next most consonant. The least consonant are the minor second (16:15), the major seventh (15:8), and the tritone (45:32). These intervals and their ratios are shown in Table 1. The ordering along the dimension of consonance corresponds quite closely to the size of the integers in the ratios (Vos & van Vianen, 1984).

An acoustic basis exists for this relationship between consonance and simple ratios of fundamental frequencies. When the ratios are simple, the harmonics of the two tones either coincide or are sufficiently distant not to interfere. Interference between tones occurs whenever the ratio of the frequencies is less than approximately 1.2 (a minor third). When the ratio is more complex, some of the harmonics are close but not exactly the same. Helmholtz (1863/1954) proposed that dissonance occurs because these near frequencies cause beats, an oscillation in amplitude that is produced by two slightly different frequencies. Subsequent formulations (e.g., Plomp & Levelt, 1965) emphasized sensory interference between frequencies within a small range called the critical band, rather than beats, as the cause of dissonance. Precise quantitative models based on this idea recover the subjective ordering of musical intervals along the dimension of consonance (see, e.g., Hutchinson & Knopoff, 1978; Kameoka & Kuriyagawa, 1969a, 1969b).

A diatonic scale consists of a subset of the tones of the chromatic scale. The pattern of major seconds (M2) and minor seconds (m2) between successive tones above the tonic (in major scales) is M2, M2, m2, M2, M2, M2, m2. When one considers all possible pairs of tones within the diatonic scale, there are a total of two

Table 1
Chromatic Scale

Tone	Frequency in equal-temperament (Hz)	Name of interval with C_4	Frequency ratio with C_4	Simple integer approximation
C_4	262	Unison	1.0000	$1:1 = 1.0000$
$C\sharp_4/Db_4$	278	Minor second, m2	1.0595	$16:15 = 1.066$
D_4	294	Major second, M2	1.1225	$9:8 = 1.1250$
$D\sharp_4/Eb_4$	312	Minor third, m3	1.1892	$6:5 = 1.2000$
E_4	330	Major third, M3	1.2599	$5:4 = 1.2500$
F_4	350	Perfect fourth, P4	1.3348	$4:3 = 1.3333$
$F\sharp_4/Gb_4$	371	Tritone, TT	1.4142	$45:32 = 1.4063$
G_4	393	Perfect fifth, P5	1.4983	$3:2 = 1.5000$
$G\sharp_4/Ab_4$	416	Minor sixth, m6	1.5874	$8:5 = 1.6000$
A_4	440	Major sixth, M6	1.6818	$5:3 = 1.6667$
$A\sharp_4/Bb_4$	467	Minor seventh, m7	1.7818	$16:9 = 1.7778$
B_4	495	Major seventh, M7	1.8877	$15:8 = 1.8750$
C_5	524	Octave	2.0000	$2:1 = 2.0000$

minor seconds (or equivalently within the octave, major sevenths), five major seconds (minor sevenths), four minor thirds (major sixths), three major thirds (minor sixths), six perfect fourths (perfect fifths), and one tritone. The most frequently appearing interval, the perfect fourth (perfect fifth), is the most consonant, and the least frequently appearing intervals, the minor second (major seventh) and the tritone, are the least consonant. Other scales with a prevalence of consonant intervals include harmonic and melodic minor scales, the Japanese Ritsu mode, the common pentatonic scale, and the common "blues" scale (Huron, 1994). This suggests an effect of consonance on the formation of scales. Similarly, the tendency to form harmonies of relatively consonant intervals such as thirds and fifths reflects the perceptual attribute of consonance.

Tuning and intonation. Another topic treated in the tradition of Helmholtz is tuning and intonation. As has long been recognized, tuning systems cannot be constructed such that all intervals are tuned to the theoretical simple ratios (Burns & Ward, 1982; Hall, 1973; Helmholtz, 1863/1954; Rasch, 1984). Equal temperament has the advantage of permitting modulation and transposition, but some intervals are quite far from their theoretical values. For example, minor thirds are flat (by 16 cents, where a cent is $\frac{1}{100}$ of a semitone), and major thirds are sharp (by 16 cents). Nonetheless, because of its practical advantages, equal temperament has been accepted as a reasonable approximation to simple ratios. Table 1 shows the frequencies of chromatic scale tones in the octave C_4 to C_5 in equal-tempered tuning (based on $A_4 = 440$ Hz). The fourth column gives the ratios of the frequencies of successive tones ($C\#_4/Db_4$, D_4, $D\#_4/Eb_4$, etc.) with the frequency of the first tone of the scale, C_4. These are calculated as follows: $\sqrt[12]{2} = 1.0595$, $(\sqrt[12]{2})^2 = 1.1225$, $(\sqrt[12]{2})^3 = 1.1892$, etc. Many of these can be closely approximated by ratios of small integers as shown in the last column of Table 1.

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. Tuning judgments are somewhat more precise for smaller intervals and more consonant intervals (Hall & Hess, 1984). Detection of mistuning can be attributed largely to the strength of beats produced by tempered intervals (Vos, 1982, 1984, 1986, 1988; Vos & van Vianen, 1984, 1985). However, experiments with dichotic stimuli (two tones to different ears that produce no beats) suggest that musicians can also use internal interval standards to make tuning judgments (Hall & Hess, 1984). Consistent with this is the finding that tuning preferences for melodic intervals (which also do not produce beats) are similar to those for harmonic intervals (Rasch, 1985). An unusual approach to studying consonance used specially constructed tones with stretched harmonics (Mathews & Pierce, 1980). The distance between harmonics was expanded by a constant multiplicative factor. When the harmonics coincided, a sensation of finality or consonance resulted. Similar results were found for chords formed with nonstandard ratios of fundamental frequencies, 3:5:7 and 5:7:9 (Roberts & Mathews, 1984). Using novel stimuli such as these has the advantage of studying psychoacoustic properties while minimizing the influence of experience or learning. In sum, studies of musical interval tuning suggest that beats caused by harmonics close in frequency have the major influence on tuning judgments.

In musical practice, performers often deviate, sometimes markedly, from theoretical tuning values (equal-tempered, just, or Pythagorean intonation). This is found for singers and players of non-fixed-pitched instruments (Fyk, 1995; Francès, 1958/1988; Rakowski, 1990; Rakowski & Miskiewicz, 1985; Shackford, 1961, 1962; and other studies summarized in Ward, 1970; Gabrielsson, 1999). Intervals (including the octave; Ohgushi, 1983; Sundberg & Lindqvist, 1973) tend to be stretched compared with their theoretical values, except for minor seconds, which tend to be compressed. These deviations may be conditioned by context and serve expressive purposes. For example, when a tritone is notated as an augmented fourth, it tends to be played larger than when notated as a diminished fifth (Rakowski, 1990; Fyk, 1995). In violin performances, only 11% of intervals agreed with just intonation, Pythagorean intonation, or equal temperament, and most intervals appeared in three variants depending on the melodic and harmonic context (Fyk, 1995). Intonation is also adjusted at the beginning of a tone, and the final portion exhibits a tendency toward the following tone that may enhance melodic coherence. Rapoport (1996) proposed a typology of expressive variations in opera singing. Features include onset of voicing, onset of upper harmonics, vibrato, gradual and abrupt transitions between onset and steady-state portions of a tone, and other pitch changes within a tone. These observations about tuning suggest that the simple-ratio theory of consonance has limits in how strictly it constrains musical performance and that it is modified by context and expressive intent.

Implications of basic research for pitch patterns in music. To summarize to this point, listeners are highly sensitive to small differences in pitch. However, pitch differences used in music are much larger than the just detectable difference. Moreover, musical pitch is based on a series of relatively widely separated pitches in the musical scale. Intervals are far more important than the absolute pitch level. Intervals found in Western music (as well as music in many other cultures) show an influence of acoustics, particularly the harmonic structure of complex tones, on the selection of pitch combinations. The research agenda set by Helmholtz (1863/1954) provides important insights into physical acoustics of musical instruments and how these are processed by the sensory system. Understanding the structure of complex tones and their effects on hearing provides an explanation for the perceptual dimension of consonance. The harmonic structure of tones also gives a framework for understanding the construction of scales and harmonies, particularly in Western tonal-harmonic music.

Helmholtz (1863/1954) recognized the limitations of this approach in accounting for many musical phenomena. He considered the relation between these scientific observations and musical practice as follows:

> The construction of scales and of harmonic tissue is a product of artistic invention, and by no means furnished by the formation or natural function of our ear, as it has been hitherto most generally asserted. Of course the laws of the natural function of our ear play a great and influential part in this result; these laws are, as it were, the building stones with which the edifice of our musical system has been erected. ... But just as people with differently directed tastes can erect extremely different kinds of buildings with the same stones, so also the history of music shews us that the same properties of the human ear could serve as the foundation of very different musical systems. (pp. 365–366)

Research on Musical Pitch

Introduction. As with studies of rhythm, the upsurge of research on pitch in the last few decades has turned toward more complex musical issues. The findings demonstrate how cognitive rules, schemas, and categories influence the perception of musical pitch (see Krumhansl, 1991b, for additional references). A treatise by Francès (1958/1988), *The Perception of Music,* outlined the major directions the research was to take. This wideranging work considered extended musical sequences, often drawn from compositions including contemporary styles. Innovative techniques were devised to measure music's effects on perception, memory, and psychophysiology. Participants included those with high levels of musical expertise. Another influential work of the same period was Meyer's (1956) *Emotion and Meaning in Music.* This work integrated diverse psychological literatures, including Gestalt psychology, motivation and emotion, learning, and information theory as they relate to the perception of music. It stressed the central role of expectation, generated from both general principles of perceptual organization and learned style patterns, in the experience of music. The review that follows generally moves from simple to more complex and musically realistic materials.

Absolute pitch. Absolute pitch (AP) is defined as the ability to name a sounded pitch or to produce a pitch in response to a note name. It is contrasted with relative pitch (RP), the ability to identify notes relative to sounded reference pitch(es). The term *perfect pitch* is sometimes used instead of AP but is misleading because accuracy varies across musicians with AP (from 30–100% in studies reviewed by Takeuchi & Hulse, 1993). Possessors of AP name pitches rapidly and without effort or conscious strategy. Some additional musicians may name pitches relative to a remembered standard pitch (such as A_4, 440 Hz). This can be improved with training (Cuddy, 1968, 1970) but is not strictly speaking AP.

The comprehensive review of AP by Takeuchi and Hulse (1993, which should be consulted for additional references; see also Ward & Burns, 1982) finds an accuracy limit of approximately .2 semitones (20 cents) in both naming and production tasks. However, some listeners who name pitches accurately fail in production tasks. Accuracy tends to fall off in low and high registers and to be better for familiar-sounding tones (the musician's primary or first-learned instrument) than pure (sine wave) tones. Of the errors made by AP listeners, many are indicating the wrong octave rather than the wrong pitch class (C, C♯, D, etc.).

Memory tasks find that pitch memory is approximately equal for possessors and nonpossessors of AP for delays up to one minute, but only AP possessors perform above chance for longer delays. Various findings implicate verbal codes: reduced performance for very high pitches (which have weaker musical qualities; Bachem, 1954), pitches that fall between tones of the chromatic scale (Rakowski, 1972), pitches with linear spacing (which prohibits labeling in contrast to the normal logarithmic spacing; Cuddy, 1982), and interference by other verbal material (Barnea, Granot, & Pratt, 1994; Zatorre & Beckett, 1989).

An early-learning hypothesis is the primary focus of recent theorizing about the etiology of AP (Takeuchi & Hulse, 1993). The hypothesis states that AP can be learned most easily during a limited period of development, possibly comparable to a critical period for language learning. Various studies find a relatively high incidence of AP among musicians who began music lessons before the age of about six years. In contrast, estimates in the general population are as low as 0.01% (Bachem, 1955), although the lack of a standardized test should be emphasized. Moreover, among possessors of AP, a negative correlation is found beteween AP accuracy and the age of first music lessons (Miyazaki, 1988; Sergeant, 1969). Several articles report that young children can be taught AP, and Crozier (1997) recently showed a learning advantage for children over adolescents.

A finding that may be related to the early-learning hypothesis is that white-key notes are more accurately and rapidly identified than black-key notes (Miyazaki, 1989, 1990, 1995; Takeuchi & Hulse, 1991). Marvin and Brinkman (1999) extended this to excerpts from pieces (as opposed to isolated tones) and showed, somewhat surprisingly, that musicians without AP were also more accurate identifying the tonality (key) of excerpts with white-key tonics. This ties into the early-learning hypothesis because of the preponderance of white-key pitches in the early repertoire of piano students. White-key notes are also more frequent in the repertoire in general. This frequency distribution may facilitate access to the white-key notes, just as frequency distribution facilitates access to common words.

These observations leave open the question of the precise mechanisms involved in AP. The currently available evidence does not strongly support an association between AP and better pitch discrimination thresholds, echoic memory, or tinnitus in possessors. Confounds between inheritance and environment prevent simple conclusions concerning a possible genetic basis for AP. Recent research by Gregersen (1998) and Gregersen, Kowalsky, Kohn, and Marvin (1999) points to a genetic basis, however. The rate of AP in siblings of individuals with AP is approximately 25%, compared with a rate of 1–2% in siblings of musicians without AP. Genetic modeling suggests a major gene is acting recessively.

A number of studies have found differences in brain activity between AP possessors and nonpossessors. Klein, Coles, and Donchin's (1985) AP participants processed pitches without producing a P300 event-related potential. Hantz, Crummer, Wayman, Walton, and Frisina (1992) found that the P300 potential was reduced in size and latency for AP listeners during pitch discrimination tasks, suggesting that they performed comparisons in long-term rather than in working memory. The brain distributions of the P300 potential were different in AP possessors and nonpossessors in the study by Barnea et al. (1994). However, Tervaniemi, Alho, Paavilainen, Sams, and Näätänen (1993) found no effect of AP ability on the mismatch negativity that typically accompanies presentation of physically deviant auditory stimuli. In a study of neuroanatomy, Schlaug, Jäncke, Huang, and Steinmetz (1995) reported structural brain asymmetries, with exaggerated left-sided asymmetry in the planum temporale region of the posterior perisylvian region. These preliminary results encourage further investigation of brain physiology and anatomy in AP possessors.

Another finding in recent research is the appearance of a weak form of AP, sometimes called *absolute tonality.* Terhardt and Ward (1982) found that musicians who were given a simplified score could detect transpositions in piano performances; transpositions of just one semitone were detected with above-chance accuracy by most of the musicians, even those who did not possess AP as it is normally defined. Terhardt and Seewann (1983) replicated this result and extended it to electronic sounds, eliminating piano timbre as a clue to transposition. Marvin and Brinkman's

(1999) musicians without AP were also more accurate identifying the tonality of excerpts than isolated tones. Finally, in production measures, Halpern (1989) found AP nonpossessors consistently sang familiar songs starting on the same pitch over several days, and Levitin (1994) found quite good matching (51% within one semitone) to the original pitch of recorded popular sounds in a group drawn from the general population.

A question requiring further systematic study is the kind of musical situations in which AP is advantageous or disadvantageous. Takeuchi and Hulse (1993) suggested that AP may be especially advantageous for performing music in styles, such as atonal music, that lack stable reference pitches. However, it may be disadvantageous for performing transpositions (Revesz, 1953; Ward, 1963). Of course, AP possessors develop RP and can use this ability somewhat independently of AP. For example, Benguerel and Westdal (1991) demonstrated AP musicians can identify intervals directly without deriving interval identifications from AP information. Studies by Miyazaki (1988, 1992, 1995), however, found AP possessors were impaired in accuracy and speed of identifying intervals when the reference tone was mistuned so that it fell between pitch classes, suggesting interference by AP processing.

Categorical perception. Listeners perceive pitch categorically as intervals of the musical scale. In one experiment (Burns & Ward, 1978), musically trained listeners labeled melodic intervals (with the two tones of the interval sounded in succession). The intervals ranged from 250 to 550 cents in steps of 12.5 cents. The listeners abruptly shifted between interval labels. That is, the smallest intervals were almost always labeled minor third, the medium sized intervals were almost always labeled major third, and the largest intervals were almost always labeled perfect fourth. (When additional quarter-tone response labels were added, listeners did not use them consistently, suggesting that these results did not simply result from restricting the response labels available to traditional interval names.) Moreover, performance in the discrimination task, which required listeners to judge which of two intervals was wider, was close to predictions from the identification data. In other words, intervals were discriminated only to the extent that they were labeled differently, producing peaks in discrimination performance at the category boundaries. Consistent with the idea that categorical perception of musical intervals results from musical experience, no such peaks occurred for musically untrained listeners. Related research comparing listeners with and without AP was reported by Burns and Campbell (1994).

Similar results appear in other studies. Musicians exhibited the following: (a) sharp identification boundaries, (b) discrete steps in magnitude estimates (judgments of the size of the intervals on a numerical scale) corresponding to interval category boundaries, and (c) an inability to distinguish "sharp" from "flat" intervals within categories (Siegel & Siegel, 1977a, 1977b). Categorical perception also extended to harmonic intervals (with the two tones of the interval sounded simultaneously), but with these intervals, discrimination performance exceeded predictions based on identification scores (Zatorre & Halpern, 1979). Intervals presented at the end of a tonal melody were also perceived categorically (Wapnick, Bourassa, & Sampson, 1982), so the effect is not an artifact of judging isolated intervals. In a result suggesting that context may even enhance categorization, listeners failed to detect mistuning when it conformed to the melodic and harmonic tendencies of

the tones in the musical context (Francès, 1958/1988). Nonmusicians exhibited neither sharp categorical boundaries nor peaks in the discrimination functions (Howard, Rosen, & Broad, 1992). This again suggests that the interval categories are learned through experience.

A cross-cultural study supports the importance of experience. Expert Javanese and Western musicians judged interval size (Perlman & Krumhansl, 1996). Javanese music is unusual in that two different tuning systems, pélog and sléndro, coexist. Some Javanese musicians showed assimilation to pélog tuning, others to sléndro tuning. Some Western musicians showed assimilation to the diatonic scale. However, in this study, other Western musicians made extremely accurate judgments. This, coupled with accurate judgments by musicians in studies of tuning, suggests that information about how intervals deviate from tuning norms is retained at some level of processing despite categorization at other levels.

Models of pitch organization. Theoretical models of pitch organization are directed at describing the mental representation of the listener. Some of these models are intended to describe the organization of the string of musical events that constitutes a piece of music. Other models are intended to describe general relationships that occur among the elements used in music, such as tones, chords, and keys. This distinction was introduced (Bharucha, 1984b) in the contrast between event hierarchies, on the one hand, and tonal and harmonic hierarchies (described later), on the other. The models below draw on a variety of formal systems.

One idea influencing cognitive research on music is that the listener's mental representation of music can be formalized by a set of rules. Simon and Sumner (1968) articulated the basic premises of this approach. First, the purpose of such rules is to enable listeners to develop expectations for successive events (pattern induction). Second, the rules operate on small and well-defined sets of elements ("alphabets" such as the chromatic scale, diatonic scale, and triads). Third, the rules can be described using a 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 with different alphabets and operators possible at different levels. Finally, musical patterns exist simultaneously in multiple dimensions (metric, rhythmic, melodic, harmonic). Deutsch and Feroe's (1981) model elaborated these proposals in their coding model of pitch. Supporting experimental results showed that tonal sequences with a hierarchical, rule-governed organization were more accurately recalled than were unstructured sequences (Deutsch, 1980). In addition, recall was impaired when rule-governed sequences were subjected to inappropriate temporal segmentation.

Another class of models draws more directly on linguistics. Lindblom and Sundberg (1970) proposed a theory patterned after Chomsky's (1968) theory of language, which seeks to answer the question "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?" Illustrating this approach, they applied rules of linguistic prosody to a set of Swedish nursery tunes, noting that the procedures for deriving stress and prominence contours in a tree diagram are similar in music and language. The system of prominence rules was also used to generate novel but stylistically similar melodies, as well as variations of a folk melody (Sundberg & Lindblom, 1976).

To date, the most extensive and influential model applying linguistic concepts to music is found in Lerdahl and Jackendoff's (1983) *A Generative Theory of Tonal Music*. Two components of the model represent the cognitive representation of musical events. The time-span reduction component assigns a tree structure specifying the relative dominance of each surface event. The prolongation reduction component provides a description, also in the form of a tree, of patterns of harmonic tension and relaxation. Both trees represent subordinate versus superordinate relations between events at each level of the tree. Empirical support exists for both components. Predictions of the time-span reduction conformed to listeners' judgments of phrase endings for two musical excerpts from Mozart and Bach (Palmer & Krumhansl, 1987a, 1987b). Another study found evidence that listeners abstract the underlying harmonic structure as formalized in the prolongation reduction (Bigand, 1990). Additional perceptual support for prolongation reductions in tonal music was obtained by Dibben (1994), but that study suggested that similar hierarchical descriptions may not extend to atonal music.

Another class of pitch models is geometric. These describe general relations among the elements of music. The strong perceptual equivalence of tones at octave intervals has motivated pitch models in the form of an ascending spiral (and variants of it). Tones at octave intervals are located one above the other as the spiral wraps around. The circular component is called the *chroma circle*. Supporting perceptual data come from using specially constructed tones (Shepard, 1964). Each tone consists of ten sinusoidal components at octave intervals. For example, one tone might consist of Cs sounded in 10 octaves, another of C♯s sounded in 10 octaves, and so on. The amplitudes at the extremes of the range are close to threshold, whereas those in the center are well above threshold. Sounding 12 such tones in succession (with components filling in at the bottom of the range as components drop out at the top) produces the perception of an unbroken succession of steps returning to the beginning. Hence, the perceptual dimension is circular, and so the tones are called *circular tones*.

In an experiment using these tones, listeners judged two circular tones as ascending or descending depending on the direction in which the components were closer (Shepard, 1964). Two tones with equal distances in the two directions (the tritone) were ambiguous. Some listeners heard the pair as ascending, others as descending. Further research suggested that the direction can be influenced by context, so that a C–C♯–F♯ sequence would be heard as ascending and a C–B–F♯ sequence as descending (Shepard, 1983). Deutsch (1986a) has claimed that there are stable individual differences in the point on the chroma circle where the break occurs between ascending and descending perceptions, possibly related to language learning (Deutsch, 1991), but this has not been supported by subsequent research (Repp, 1994). Additional evidence for the spiral model comes from a multidimensional scaling study in which similarity judgments of tones were transformed into a geometric representation (Ueda & Ohgushi, 1987). Various generalizations of the circular tone concept have also appeared (Allik, Dzhafarov, Houtsma, Ross, & Versfeld, 1989; Burns, 1981; Nakajima, Tsumura, Matsuura, Minami, & Teranishi, 1988). Other geometric models (summarized in Krumhansl, 1990a; Shepard, 1982a, 1982b) include additional dimensions corresponding to the circle of fifths (on which neighboring tones are

separated by perfect fifths, . . . E♭, B♭, F, C, G, D, A, E, . . .) and cycles of major thirds (e.g., C, E, A♭).

The coding, linguistic, and geometric models just summarized provide theoretical frameworks for some of the empirical research on pitch perception. However, the majority of recent research has addressed one or another aspect of music theory. The empirical research has investigated whether pitch structures, such as scale, harmony, and key, influence how sequences of pitches are encoded and remembered. Underlying this approach is the notion that the kinds of descriptions theorists have derived from extensive analysis of music are similar to the kinds of cognitive representations listeners have abstracted through their musical experience. This suggests that familiarity with the musical style, the age of the listener, and the extent of musical training all affect the degree to which the experimental data conform to the theoretical predictions. Alternatively, convergence between theoretical descriptions and psychological results may occur because psychological abilities to process pitch structures constrain the formation of musical patterns and consequently the regularities codified in music theory.

Tonal hierarchies. Pitches in tonal contexts are hierarchically differentiated. One experimental method, called the probe-tone technique (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979), sounds a context establishing a key (such as its scale or a chord cadence) that is followed by a single tone. Listeners rate how well the tone fits with the context (variants of the instructions appear in different experiments). In rough categorical terms, the first tone of the scale (tonic) heads the hierarchy, followed by the fifth scale degree (dominant) and the third scale degree (mediant), then the remaining scale degrees, and finally the nondiatonic tones. The hierarchy appears in other measures: the perceived similarity of tones in tonal contexts (Krumhansl, 1979, 1990a), temporal order asymmetries in similarity judgments and memory confusions (Krumhansl, 1979, 1990a), reaction times in judging key membership (Janata & Reisberg, 1988), judgments of phrase endings (Palmer & Krumhansl, 1987a, 1987b), expectations for melodic continuations (Krumhansl, 1995a; Schmuckler, 1989; and other studies cited below), and accuracy of naming tones by listeners with AP (Miyazaki, 1989). Moreover, these psychological measures correlate strongly with the distribution of tones (how frequently they occur) in tonal-harmonic music (Krumhansl, 1985, 1990a), suggesting the tonal hierarchies are learned through experience.

Two cross-cultural studies found style-appropriate tonal hierarchies in non-Western music: North Indian music (Castellano, Bharucha, & Krumhansl, 1984) and Balinese music (Kessler, Hansen, & Shepard, 1984). In the former, the data of (South Asian) Indian and American listeners were remarkably similar. This result may depend on the fact that the contexts preceding the probe tones were relatively complex and explicitly emphasized the structurally important tones through the drone and the repetition and extended durations of certain tones. Thus, listeners may have abstracted tonal hierarchies from unfamiliar styles based on the distribution of tones in the music. A study using specially composed sequences supported this possibility (Oram & Cuddy, 1995). The context sequences were composed so that one tone occurred eight times, two others four times, and four others once each. These were called *tone sets*, some of which conformed to diatonic structure whereas others did not. In all cases, the probe-tone ratings reflected the frequency of tones in the context. A related finding is

that listeners unfamiliar with atonal music also were influenced by tone distributions (and how recently tones were sounded in the context) in judging probe tones with atonal contexts (Krumhansl, Sandell, & Sergeant, 1987). Thus, tone distributions psychologically establish tonal hierarchies in the absence of extensive experience with the style.

Models of key-finding. The results just described suggest that listeners may use tone distributions to determine key when listening to music. To examine this possibility, Krumhansl and Schmuckler (Krumhansl, 1990a) constructed an algorithm that matches (by correlation) the tone distributions in musical samples to the experimentally measured tonal hierarchies of major and minor keys (Krumhansl & Kessler, 1982). The algorithm was highly accurate when applied to excerpts from Bach's *Well-Tempered Clavier,* outperforming Cohen's (1991) music students, and was able to model experts' judgments of modulations in a Bach prelude. It performed less well on short excerpts of Chopin's preludes. Another model of key-finding (Longuet-Higgins & Steedman, 1971) works by progressively eliminating keys on the basis of whether or not the tones in the musical sample are contained in the diatonic major and minor scales. This model was less accurate than Krumhansl and Schmuckler's algorithm on the Bach preludes, suggesting that tonal hierarchies yield information over and above key membership. Temporal order, harmonic structure, and rhythmic and metrical stress would probably also enhance such algorithms.

Another proposal (Butler & Brown, 1984; Brown, Butler, & Jones, 1994) concerning key-finding derives from the observation by Browne (1981) that tritones and minor seconds are relatively rare in the set of diatonic scale tones. Thus, listeners may use these intervals to determine key. To date, an algorithm based on this possibility has not been tested. Various observations (Krumhansl, 1990b) suggest that the tritone has limited utility for key-finding, including that it is relatively rare as a melodic or harmonic interval and is difficult to encode and remember. Moreover, tonal contexts containing tritones have weak tonal implications (Cuddy & Badertscher, 1987; Krumhansl, 1995a). Similarly, Butler and Brown (1984) showed that listeners were less accurate identifying possible tonics when a three-tone context contained a tritone than when it contained three other scale tones. Minor seconds, on the other hand, have relatively strong tonal implications (Krumhansl, 1995a), appear frequently in melodies, and are easily encoded and remembered, and so provide good cues to key. Showing the importance of minor (and major) seconds, neighboring tones on chromatic (and diatonic) scales determined harmonic and tonal implications of melodic sequences (Bharucha, 1984a). This was formalized as Bharucha's melodic anchoring principle, subsequently elaborated as a quantitative model and supported by an analysis of a Mozart piano sonata (Bharucha, 1996).

Finally, a neural network model has successfully modeled key-finding (Leman, 1995a, 1995b). This model is in the tradition of artificial intelligence models of cognitive processes. It begins with an auditory component that processes the acoustic signal and forms pitch patterns. These patterns self-organize into a stable perceptual schema during perceptual learning. The resulting information then enters a self-organizing network that consists of cognitive schemas for pitch structures. These include a schema for tone-center perception formed by long-term learning. The tone-center schema successfully identifies keys of musical excerpts.

The model synthesizes acoustic properties (harmonics of tones), processing strategies of the auditory system, and tone distributions in music (including temporal order), and emphasizes the dynamic nature of music perception.

Harmony. An essential component of Western tonal-harmonic music is the conventionalized use of certain chords and chord progressions. The basic chords usually consist of three tones (triads). Chords consisting of four (or even more) tones are also found, and some of these also play important harmonic roles. The chords usually consist of tones drawn from the diatonic scale at intervals of a third. For example, the tonic triad (denoted I) consists of the first, third, and fifth tones of the scale. The chord built on the fifth tone of the scale (V, called dominant) consists of the fifth, seventh, and second tones of the scale. The tonic triad and dominant are considered most important for establishing the key. Sometimes, the chord built on the fourth scale tone (IV) is included in this central set. The harmonic functions of the chords built on the second and sixth scale tones (II and VI, respectively) are generally considered somewhat weaker harmonically, and the chords built on the third and seventh (III and VII) play the weakest roles in defining the key. (See Krumhansl, 1990a, pp. 166ff., for more information and important qualifications.)

Experimental studies support this theoretical description of a harmonic hierarchy. This was shown in direct judgments of how well chords fit with a tonal context (Krumhansl, 1990a), in a task analogous to the probe tone task. The harmonic hierarchy also appears in similarity judgments and memory accuracy, as well as temporal-order asymmetries in these measures (Bharucha & Krumhansl, 1983; Krumhansl, Bharucha, & Castellano, 1982; Krumhansl, Bharucha, & Kessler, 1982). As with tones, the harmonic hierarchy measured experimentally correlates with chord distributions in music (Krumhansl, 1990a).

Various results suggest strong dependencies between perceived pitch structure at three levels: tones, chords, and keys. The harmonic hierarchy depends on the positions of the chord tones in the tonal hierarchy. Both tonal and harmonic hierarchies yield similar measures of the distances between keys (Krumhansl, 1990a; Krumhansl & Kessler, 1982). These distances produce a toroidal map of key relations generated by two factors: the circle of fifths and the relative and parallel major–minor key relations; this map corresponds with music-theoretic descriptions (see, e.g., Schoenberg, 1969). These distinct but interdependent levels have been elaborated theoretically in Lerdahl's (1988) pitch-space model. It contains precise quantitative values of pitch distance on three levels: pitch-class proximity (using a representation similar to tonal hierarchies of Krumhansl & Kessler, 1982), chord proximity within a key (cycle of diatonic fifths), and distances between keys or regions (cycle of fifths). This pitch-space model, together with the prolongational analysis (Lerdahl & Jackendoff, 1983), accounted well for tension judgments in a section of a Mozart piano sonata (Krumhansl, 1996).

A topic related to harmony is virtual pitch, where a pitch corresponding to a missing fundamental may be heard. The pitch is implied by the physically present pitches as part of the same harmonic series but may itself not be present. The subsidiary pitches arising from chords may increase the salience of certain tones (Terhardt, 1974) and thus play a role in the perception of the chord root. The model of Terhardt (1979; Terhardt, Stoll, & Seewan, 1982a, 1982b) has been elaborated (Parncutt, 1989) and

applied to various problems including root ambiguity (Parncutt, 1988), key finding (Huron & Parncutt, 1993), and harmonic tension (Bigand, Parncutt, & Lerdahl, 1996). The latter study also found effects of distance of horizontal motion, harmonic hierarchies (Krumhansl, 1990a), and pitch-space distances as formalized in Lerdahl's (1988) tonal pitch-space model.

Melodic organization and memory. Numerous studies show that musical structures, such as scale, harmony, and key, influence how well longer pitch sequences are remembered. Diatonic scale is important for recognizing transposed sequences (sequences that are shifted up or down in pitch). In an influential study (Dowling, 1978), a target sequence was followed by two comparison sequences. One of the comparison sequences was an exact transposition (maintaining the size of the intervals); the other was a transposition within the key (altering the size of certain intervals as required by the diatonic scale). Listeners were required to judge which of the two was the same exact melody, only transposed. Neither musicians nor nonmusicians could reliably choose the correct melody. To explain this, Dowling argued that the diatonic scale provides a framework on which the melodic contour is hung, producing the confusions with the within-key transpositions. Key-distance also affects recognition of transpositions. Near-key lures (inexact transpositions) were harder to reject than far-key lures (Bartlett & Dowling, 1980). Another result demonstrating the importance of scale structure is that memory performance was better for diatonic sequences with normal tuning, but the advantage disappeared for analogous sequences when the interval sizes were reduced by a constant (logarithmic) factor (Watkins, 1985).

An extensive series of studies by Cuddy and collaborators (Cuddy & Cohen, 1976; Cuddy, Cohen, & Mewhort, 1981; Cuddy, Cohen, & Miller, 1979; Cuddy & Lyons, 1981; Dewar, Cuddy, & Mewhort, 1977) has studied recognition accuracy for transposed sequences. These studies expanded 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). Bach chorales and harmonization exercises were used to investigate the perception of modulation distance (Cuddy & Thompson, 1992; Thompson, 1993; Thompson & Cuddy, 1989, 1992, 1997). Included among the findings are accurate performance for both single voices and four-voice harmony, directional asymmetries on the cycle of fifths for harmonic sequences (shorter perceived distance in the clockwise direction), partial independence between melodic and harmonic structures, and influences of performance expression. These results show that memory for musical sequences is governed by many factors, some complex and subtle, and that traditional concepts in music theory generate testable predictions for memory performance.

Other transformations have also been examined. Numerous studies, often influenced by Dowling's (1978) article, have found that changes of pitch contour are relatively easy to detect. To some degree, listeners were able to recognize melodic invariance under transformations of inversion, retrograde, and retrograde inversion (Dowling, 1972; Francès, 1958/1988; Krumhansl, Sandell, & Sergeant, 1987). Listeners could abstract a prototypical melody from transformed versions of it (Carterette, Kohl, & Pitt, 1986; Welker, 1982). The transformations in the first study included inversion, syncopation, reduction of interval size, temporal elaboration, and deletion of a measure from the prototype. The second study in-

cluded octave displacements (changing contour), altered intervals (preserving contour), changed dynamics, and changed note duration. Both studies found regular effects of the degree of transformation. With experience, listeners came to distinguish between variations of two themes from a Liszt piano sonata, as reflected in both similarity and classification measures (Pollard-Gott, 1983). Excerpts with the same hierarchical analysis (Schenker, 1979) were perceived as similar despite extensive surface alterations (Serafine, Glassman, & Overbeeke, 1989). Finally, psychological evidence for a hierarchy of themes (or "topics") was found in chamber music pieces by Mozart and Beethoven corresponding to a music-theoretical analysis of these pieces (Krumhansl, 1998). Together, these studies show that listeners are capable of developing quite abstract cognitive representations of melodies.

Melodic expectancy. Experimental research has also studied musical expectancy. In a series of studies by Carlsen and collaborators (Carlsen, 1981; Carlsen, Divenyi, & Taylor, 1970; Unyk & Carlsen, 1987), listeners heard two successive tones (ranging from a descending octave to an ascending octave). They were instructed to sing what they believed would be the continuation of the melody had it not been interrupted. Each stimulus interval resulted in multiple responses, suggesting that expectancies select a set of tones rather than a single tone. The tones produced tended to be proximate to the second of the two context tones, except that large descending intervals resulted in a number of relatively large ascending intervals. Response tones frequently returned to the starting pitch of the context interval or to the tone that would complete the octave. A similar method was used in subsequent studies (Cuddy & Lunney, 1995; Krumhansl, 1995a) except that the two-tone contexts were followed by a probe tone, which was judged as to how well it matched the listener's expectancy. The ratings showed effects of tonal hierarchies of implied keys, melodic direction, proximity, and consonance. Production and perception measures showed general agreement (see especially Thompson, Cuddy, & Plaus, 1997).

Experimental results have been used to test various music-theoretic proposals. One such proposal, Narmour's (1990) implication–realization model, describes a core set of principles governing melodic expectation. These principles, based on Gestalt principles such as proximity and good continuation, are expressed precisely in musical interval sizes permitting experimental tests. Partial support for the model was found in the studies cited above (Cuddy & Lunney, 1995; Krumhansl, 1995a) as well as a study using melodic contexts from British and Chinese folk music and atonal music (Krumhansl, 1991a, 1995b). The results were largely independent of the listeners' musical training and familiarity with the style, suggesting the existence of general psychological principles governing melodic expectancy. Various proposals have been made for revising the model based on reanalysis of these data (Schellenberg, 1996, 1997), data from two-tone contexts (Krumhansl, 1995a), and data from Finnish spiritual folk hymns (Krumhansl, Louhivuori, Toiviainen, Järvinen, & Eerola, in press) and North Sami yoiks from Lapland (Krumhansl, et al., 1999). Judgments of melodic continuations of a Schumann song showed influences of tonal-harmonic structure as well as Meyer's (1973) linear (conjunct motion) and gap-fill (disjunct motion) patterns (Schmuckler, 1989). Similar results were obtained in a performance study in which participants improvised continuations on the keyboard (Schmuckler, 1990). Evidence for Meyer's melodic ar-

chetypes has also been found in similarity and classification mea-
sures (Rosner & Meyer, 1982, 1986).

The most temporally precise measures of expectancy come from
experiments by Bharucha and collaborators (Bharucha & Stoeckig,
1986, 1987; Tekman & Bharucha, 1992). They used a priming
paradigm in which a "target" chord was presented following
another chord, called the "prime." The task was to judge whether
the target chord was or was not in tune, an indirect measure of the
perceived relatedness between the prime and target chords. The
reaction time was shorter when the prime and target chords be-
longed to the same diatonic collection than when they did not. This
and other research has led to the development of models of musical
expectancy that are implemented as neural networks (Bharucha,
1987, 1991, 1999; Bharucha & Olney, 1989; Bharucha & Todd,
1989). These models contain "nodes" representing tones, chords,
and keys. Activation spreads through the network in a way that
simulates how learning alters neural connections. This work makes
the useful distinction between "schematic" expectations, ab-
stracted from large numbers of sequences, and "veridical" expec-
tations, instance-based expectations for what will occur next in a
particular sequence.

A number of recent studies have investigated musical expect-
ancy with event-related brain potentials. Incongruous notes or
chords elicited late positive potentials (Besson & Faïta, 1995;
Janata, 1995). These were not significantly different from re-
sponses to syntactic incongruities in language (Patel, 1998; Patel,
Gibson, Ratner, Besson, & Holcomb, 1998), suggesting that sim-
ilar neural resources may be used for processing structural aspects
of language and music even though the specific processes are
different. Another study (Besson, Faïta, Peretz, Bonnel, & Requin,
1998) found independence of semantic and tonal processing. Op-
era excerpts ended with words that were either semantically con-
gruous or incongruous and either tonally congruous or incongru-
ous. The results demonstrated the independence of lyrics and
melody. These techniques promise new insights into the neural
substrates for music and similarities and differences between mu-
sic and language (see also Marin & Perry, 1999).

Melodic organization and rhythm. Both theoretically and em-
pirically, pitch and rhythm tend to be treated separately. Clearly,
both aspects affect music perception and memory, but the rela-
tionship between them is less well understood than their separate
effects. One question that arises is whether the two components are
truly interactive or simply have additive effects in the sense that
the joint effect of the two components is the sum of their separate
effects. A number of studies support the latter possibility. Analysis
of judgments of melodic similarity uncovered three rhythmic and
two tonal dimensions (Monahan & Carterette, 1985). Intersubject
trade-offs between the weights for the two kinds of dimensions
suggest some measure of independence. Other findings showed
that pitch and rhythm made independent and additive contributions
to judged phrase structures (Palmer & Krumhansl, 1987a, 1987b).
Studies in cognitive neuropsychology (Peretz, 1993) suggested
rhythm and pitch are processed by separate modules, as supported
by selective impairment of one, but not the other, perceptual ability
in patients with brain damage. Other results, however, have sug-
gested more complex interactions between the components. Evi-
dence for interactions was found with crossed pairs of rhythmic
and harmonic patterns (Bigand, 1993), using a paradigm similar to
that of Palmer and Krumhansl (1987a, 1987b). Moreover, when

pitch and rhythmic patterns were out of phase, memory recall was
impaired (Boltz & Jones, 1986; Deutsch, 1980; Monahan, Kendall,
& Carterette, 1987); this effect, however, was not found by Smith
and Cuddy (1989). Although it is clear that pitch and rhythm enter
into complex relations with one another, the precise nature of their
interaction is not yet well understood. As measured in some tasks,
rhythmic structures can influence the organization of pitch infor-
mation, and pitch structures can influence the formation of rhyth-
mic patterns. The evidence to date does not suggest that one aspect
is psychologically primary.

Large-scale musical form. Finally, I review the relatively few
studies investigating the cognitive representation of large-scale
musical form. One study played Bach's *Goldberg Variations* in the
original order or in random orders (Gotlieb & Koneçni, 1985).
Listeners, some of whom were musically trained, did not prefer the
original order. When detailed ratings on adjective scales were
used, a preference for the original order appeared on only 1 of 15
scales. Another study examined the effect of whether or not a piece
began and ended in the same key (N. Cook, 1987). It used original
or modified versions of pieces by Beethoven, Liszt, Haydn, Men-
delssohn, Chopin, and Brahms. Music students did not prefer the
original version except for the shortest selection, suggesting that
the effect of tonal closure is restricted to a fairly short duration.

Other evidence demonstrates that memory for temporal order
within a piece is quite good. Both musicians and nonmusicians
were able to correctly order excerpts of a Berio sequenza after
hearing the piece (Deliège, 1989). Musicians performed somewhat
more accurately. As would be expected, confusions occurred be-
tween sections containing similar materials. Results from similar
tasks with a Schubert piece suggested that location judgments were
based more on cues abstracted from the surface than on underlying
musical structure (Deliège, Mélen, Stammers, & Cross, 1996).
Another study used two piano pieces by Mozart and Stockhausen,
of approximately 10 min, which were played twice (Clarke &
Krumhansl, 1990). Listeners then heard short excerpts of approx-
imately 15 s and were asked to indicate on a graphical scale where
the excerpt came from in the piece. Performance was only some-
what more accurate with the more stylistically familiar Mozart
piece. For both pieces, judgments departed systematically from
verticality such that segments toward the beginning and end of the
piece were mislocated in the direction of the center. Further
research is needed to understand more fully the form and content
of large-scale musical memories, but these studies clearly indicate
that music engenders complex and relatively accurate cognitive
representations.

General Discussion

Some generalizations emerge from this wealth of empirical
research. The first is the observation that the artful construction of
patterns in time and pitch gives rise not only to music of remark-
able complexity but also to highly complex psychological repre-
sentations. These exist on multiple levels, organized initially by
basic psychophysical principles, especially the encoding of rela-
tive, rather than absolute, values of duration and frequency. Even
at this level, special musical properties influence perception. The
ratios of durations in music tend toward simple ratios, such as 1:2
and 1:3. The ratios of frequencies tend toward simple ratios, such
as 1:2, 2:3, and 3:4. Correspondingly, psychological results show

assimilation to these categories. The ratios in musical pitch can be traced in part to acoustical properties of tones. The origin of ratios in musical time is less clear but may reflect the ability to perceive embedded periodicities and constraints on physically producing rhythmic responses.

Another important principle underlying rhythm is the existence of a fundamental pulse. Underlying temporal patterning in music, one often finds a basic periodic structure, and the evidence demonstrates that this structure provides a framework for perceptually organizing and remembering the events as they occur in time. The fundamental pulse approximates a rate of two events per second. That this corresponds to the rate of a number of other nonmusical behaviors suggests that a common internal oscillator may govern a variety of behaviors. This suggestion also carries with it an implied link between the perception of rhythm in music and motor performance. This link is supported by numerous parallels between measures of perception and performance of musical rhythms. The case for a corresponding fundamental interval in music perception is less clear. Although it is true that Western tonal-harmonic music is based on a set of (chromatic scale) tones that are approximately equally spaced in log-frequency, most music uses a subset of these tones containing relatively large and small intervals. Music in other cultures also exhibits scales consisting of small and large intervals, suggesting that contrasting intervals' sizes and the presence of one or more relatively large gaps may be a more common principle of pitch organization than is a fundamental interval.

Although the relative values of tone frequencies are psychologically primary as musical intervals, absolute values are interesting in connection with the phenomenon of AP. The ability to recognize (or produce) musical tones by name is relatively rare and is found exclusively among musicians, especially those with early training in music. The empirical results, including some recent results from neuroscience, suggest possible differences between musicians with and without AP. At the same time, however, methods that do not require the explicit use of pitch names show more accurate memory for AP level than has been previously thought, and this appears to extend to memory for tempo as well.

That most individuals have relatively poor memory for AP is related to another basic feature of pitch organization: tonal hierarchies. Both musically and psychologically, not all tones in a piece have equal significance. Some tones appear more frequently and for longer duration, occur in more prominent rhythmic and metrical positions, and are stressed in performance. These tones also have psychological priority; for example, they are remembered more accurately, influence melodic expectations, resist substitution by another tone, and produce a sense of finality or completion. In Western tonal-harmonic music, the tonal hierarchies are closely related to harmonic hierarchies and to key distance, but tonal hierarchies are evident in a wide range of styles cross-culturally. Psychologically, one function of tonal hierarchies is to establish a small set of reference tones with respect to which other tones can be encoded and remembered. This helps to compensate for poor absolute memory.

A hierarchy also exists for temporal patterns in tonal-harmonic music, which is organized around groups of beats. These groups correspond to musical meters such as 2/4, 3/4, 4/4, and 6/8 (groups of two, three, four, and six beats within a measure, respectively). The first beat is the most structurally important for defining the meter, and it and other relatively strong beats tend to be marked by

more frequent, longer, and more tonally stable tones, and are also accented in performance. Psychologically, metrically strong temporal positions are remembered better, resist deviations, and produce a sense of rhythmic stability or completion. Music in other styles does not always conform to metrical structure, but regularly recurring groups of relatively strong and weak beats appear quite generally across styles. As with pitch, the underlying psychological principle for metrical hierarchies derives from memory. The metrical hierarchy facilitates the formation of larger groups of events to extend the temporal range of coherent temporal units.

Both metrical and tonal hierarchies provide a kind of framework or grid that underlies musical patterns. Music consists of rhythms, melodies, and harmonies, the latter especially prominent in Western music. Perceptual principles of organization are central to how these are formed. A core set of grouping principles appears important for the formation of rhythmic and melodic patterns. These include grouping by proximity (in time and pitch), by repetition of identical or similar elements, and by formation of simple patterns. These groups are broken by pauses, shift of pitch register, and contrast of timbre, dynamics, or melodic contour. Tones that are harmonically related also tend to group together. Groups of groups appear at higher levels determined, in part, by the same principles. Complex interactions can occur between the grouping principles, with trading relationships between them. Rhythmic and melodic groups can also interact, giving rise to additional levels of musical and cognitive complexity.

Finally, musical patterns are organized into hierarchies of events to produce well-organized wholes extending over many minutes. Rhythmic and melodic patterns are differentiated by how central they are to the overall structure of an entire piece. They establish distinctive motives that are emphasized through repetition and variation, as well as establishing tonal centers and signal modulations (shifts) to other tonal centers in Western tonal-harmonic music. Other musical patterns have subordinate relations to the distinctive motives. Memory for large-scale musical form appears to be quite accurate and to be organized according to theoretically proposed event hierarchies. These depend to some extent on tonal, harmonic, and metrical hierarchies but also rely on knowledge of typical musical forms in the style and repetitions and contrasts within the particular piece. Thus, the formation of large-scale cognitive representations of music culminates from basic processes operating on more local levels combined with principles that facilitate more schematic representation of events occurring over longer spans of time.

An important theme that emerges from these generalizations is that, in various ways, the perception and cognition of music reflect how music is structured. That is, the psychological representations mirror patterns found in music, some given extensive treatment in music theory, analysis, composition, history, and ethnomusicology. Although the psychological methods do not presuppose the results of such studies, the psychological data can often be interpreted in these terms. This provides converging evidence for the kinds of descriptions arrived at through the study of music. It also provides insights into the psychological system that subserves the perception and production of music, with implications for further theoretical and analytical studies, composition, and performance. At the same time, the convergence found raises the question whether music is structured the way it is because of psychological constraints or whether the psychological representation is a result

of internalizing regularities in the music in one's experience. Undoubtedly, the answer is that influences occur in both directions, but the relative degree and conditions of influence need further explication. Studies of musical development and effects of training, as well as cross-cultural studies, are making inroads into this question.

Finally, another theme that emerges is that the psychology of music is developing within a strong interdisciplinary context. Although more paradigmatic laboratory studies on the topics reviewed here are needed, this review summarizes a strong empirical base of research on fundamental psychological processes in the perception of temporal and pitch patterns. The more urgent questions currently concern how research of this nature can be brought to bear on the various disciplines that are increasingly turning attention to music. For example, what are the implications of knowledge about music cognition for other areas of cognitive behavior? Do studies such as these provide guidance for selecting materials and tasks for research on music in neuroscience? Do psychological results inform computational modeling of music perception? What issues arise in the search for parallels between music and language? How do philosophical treatments inform empirical laboratory research? What is the biological basis for music, and what is its cultural function? It is hoped that this review provides an entry into some of the psychological literature on music, not only for psychologists but also for investigators in other disciplines. In turn, the questions arising from other disciplinary perspectives promise challenges to develop additional experimental methods and refine theoretical issues in the psychology of music.

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