Journal of Experimental Psychology:
Human Perception and Performance
1990, Vol. 16, No. 4, 728-741

Copyright 1990 by the American Psychological Association, Inc.
0096-1523/90/$00.75

Mental Representations for Musical Meter

Caroline Palmer
Ohio State University

Carol L. Krumhansl
Cornell University

Investigations of the psychological representation for musical meter provided evidence for an internalized hierarchy from 3 sources: frequency distributions in musical compositions, goodness-of-fit judgments of temporal patterns in metrical contexts, and memory confusions in discrimination judgments. The frequency with which musical events occurred in different temporal locations differentiates one meter from another and coincides with music-theoretic predictions of accent placement. Goodness-of-fit judgments for events presented in metrical contexts indicated a multileveled hierarchy of relative accent strength, with finer differentiation among hierarchical levels by musically experienced than inexperienced listeners. Memory confusions of temporal patterns in a discrimination task were characterized by the same hierarchy of inferred accent strength. These findings suggest mental representations for structural regularities underlying musical meter that influence perceiving, remembering, and composing music.

Perception of music, speech, and other complex human behaviors requires the processing of structured information over time. Psychological theories of serially ordered behaviors often reveal hierarchical principles of mental processing and organization that express relations among nonadjacent as well as adjacent events. Mental representations for these behaviors suggest that the complex information is recoded or organized in a form more efficient for abstract operations. A primary assumption is that the observed behavior involves complex mental processes that transform early sensory information, compare it to detailed memories, and apply decision rules to the transformed internal codes.

This theoretical framework suggests that music perception involves the recoding and organizing of musical material through reference to a more abstract system of knowledge about musical structure. This abstract knowledge often represents the underlying regularities found in one's own musical culture, such as a particular tonal system or common metrical properties. These mental structures may facilitate comprehension of global aspects of musical structure and lead to expectations about future events. Thus, tonality can provide a (pitch-based) framework for melodic expectations, and meter may provide a (time-based) framework from which temporal expectations are formed. The research described later focuses on the nature of mental representation of one important aspect of musical structure: meter. We present evidence indicating that abstract knowledge of meter affects comprehension, memory, and composition of Western tonal music.

This research was supported by a predoctoral fellowship from the National Science Foundation to Caroline Palmer, by National Institute of Mental Health Grant MH 39079 to Carol L. Krumhansl, and by a Catlin Memorial Research Grant from the Psychology Department, Cornell University.

The authors thank Mari Riess Jones and Bruno Repp for comments on an earlier draft, Roger Shepard and Edward Kessler for suggestions based on earlier related research, three reviewers, and Alison Simmons Turner, who conducted one of the experiments.

Correspondence concerning this article should be addressed to Caroline Palmer, Psychology Department, Ohio State University, 1885 Neil Avenue, Columbus, Ohio 43210.

Meter is the periodic alternation of strong and weak accents. A metrical pattern usually contains nested hierarchical levels in which at least two levels of pulsation are perceived at once, and one level is an integer multiple of the other level. The elements that make up a metrical pattern are beats, which are equally spaced points in time, either in the form of sounded events or hypothetical (unsounded) time points (Lerdahl & Jackendoff, 1983). In Western tonal music, metrical levels of accent are constrained by a strict nested hierarchy of binary and ternary beats, with the requirement of equal durations between beats at each level. The simplest type of metrical structure has a regular beat, marked so that every *n*th occurrence of a beat (two, three, or a simple multiple of these) is accented. An accent marks the beginning of each metrical unit or bar, which is traditionally notated by vertical lines dividing the musical events into bars. Meter is also notated by time signatures; for instance, the time signature of $\frac{3}{4}$ meter signifies that the primary accent occurs on every third beat (indicated by the numerator) and the beats are quarter-note durations (indicated by the denominator; Apel, 1972).

One of meter's primary functions is to contribute to rhythmic organization in music. Generally, rhythm is the whole feeling of movement in time, including breathing, pulse, phrasing, tonality, and meter (Apel, 1972; Lerdahl & Jackendoff, 1983). More commonly, rhythm refers to a group of musical events containing one accented event and one or more unaccented events (Cooper & Meyer, 1960). Such a pattern of events acquires a particular rhythmic interpretation through its relationship to the meter (Cooper & Meyer, 1960; Sloboda, 1985). Thus, the same rhythmic pattern may be interpreted differently in different metrical contexts, and the same meter can support different rhythms (Cooper & Meyer, 1960). The role of meter in rhythmic organization is the focus of this study.

Metrical structure serves many other functions in music perception and production, as well as contributing to a sense of rhythmic organization. The most obvious role of meter is to allow a way of measuring time, so a performer or listener can reproduce or recognize the same set of temporal relations from one performance to another as well as within different sections of the same performance. Another function is to aid the perception of groups by partitioning musical time into segments (Benjamin, 1984). Meter can aid the organization of time-points into equivalence classes by means of periodic partitioning at several levels (Lewin, 1984). Just as pitch events form equivalence classes (for instance, pitches with 2:1 frequency ratios are octave equivalent and serve similar structural functions), meter creates time-points, and events occurring at these time-points can form equivalence classes (Benjamin, 1984). Thus, the first beat of each bar defines an equivalence class, as does the second, the third, and so on. Metrical equivalence classes may be important psychologically; perceived similarity and memory associations may be higher within than between equivalence classes. For instance, evidence from similarity ratings indicate that a shared meter accounts for most of the perceived relatedness between simple rhythms, melodies, and dance music (Gabrielsson, 1974; Monahan & Carterette, 1985). These descriptions indicate some of the possible psychological roles of meter in music perception; the next section examines music-theoretic notions of meter and their implications for a psychological theory of music perception.

Music-Theoretic Notions of Meter

Music theorists disagree as to whether meter is defined by the phenomenal accents perceived in music or by mental structures (inferred accents not necessarily contained in the musical material). Some believe meter is defined by perceived accents; meter is partitioning on the basis of accent (Berry, 1976); accents are those pulses that are stronger than others or marked for consciousness (Meyer, 1956). Others claim that meter's role is to give time-points an identity independent of the tonal, motivic, or harmonic accents present (Benjamin, 1984). Thus, meter may be independent of sensory functions; instead, abstract knowledge of the periodic temporal functions that operate in Western tonal music may play a role in meter perception. One of the advantages of this second approach is that an abstract framework can provide structure for comprehension of unfamiliar music. For instance, one method of understanding music whose pitch structures are little understood is to first grasp the metrical structure, with the assumption that the meter is meant to aid comprehension of the coinciding pitch and rhythmic structures (Lewin, 1984).

Theoretical perspectives on meter also differ as to how different accent structures are combined in music. Music theorists traditionally viewed meter as linked with grouping (the way we segment the musical content on various levels; Cooper & Meyer, 1960). In this view, meter is a way of measuring time by means of regularly recurring accents, and groups are the affiliation of unaccented events to each single accented event. Thus, the same accent pattern determines both meter and grouping structure. Others take the position that meter and grouping are distinct and separable mental acts. For instance, Lerdahl and Jackendoff (1983) dissociated meter and grouping on the grounds that meter is an organization of time-points based on perception of accent, whereas grouping is an organization of events without reference to accent. A final approach holds that accent and grouping are modes of partitioning musical time and meter is imposed on the interaction of accent and grouping (Benjamin, 1984).

An important contribution to metrical theory, made by Lerdahl and Jackendoff (1983), distinguished three types of accent contributing to rhythmic organization—phenomenal, structural, and metrical—that rely, respectively, on sensory, structural, and schematic sources of evidence. Phenomenal accents arise from surface properties of the sound, such as duration, pitch height, and intensity changes. Phenomenal accents are distributed throughout the music in irregular locations. Structural accents result from more abstract musical properties that have no direct sensory correlates, and they are more regularly distributed than phenomenal accents. For instance, cadences (melodic or harmonic movements that convey the impression of a conclusion) provide structural accents; cadences are perceived as weighted, without any sensory correlates. Metrical accents arise from the existence of a mental periodic framework or schema and are quite regular. To establish a sense of meter, a listener must infer metrical accents from the phenomenal and structural accents. Thus, Lerdahl and Jackendoff's (1983) theory proposes a relationship between accent cues in specific musical experiences and the establishment of a mental schema that represents the regularities of meter. This metrical framework contributes to a listener's sense of rhythmic organization. We return to the metrical predictions of their theory for comparison with experimental findings in later sections.

Perceptual Cues for Meter

How is meter instantiated, and what determines the perception of a particular meter? The concept of preestablished mental frameworks or schemas for meter is not new; in fact, evidence suggests that, once established, the schema will resist disruption, even in the face of conflicting evidence (Longuet-Higgins, 1979). Longuet-Higgins and Lee (1982) proposed an algorithmic model for perception of meter based only on relative duration cues that groups the notes of a melody into bars, identifying the meter which established the melody's rhythm. In their processing model, listeners revise or confirm a hypothetical meter in light of subsequent events that cause them to expand the bar or move the accent locations. The most important factors causing alterations in the metrical hypotheses are the relative durations of the events and where they occur in relation to the primary beats in a bar (Longuet-Higgins & Lee, 1982).

One problem faced by models of meter perception is how to determine which musical events are accented. Longuet-Higgins and Lee's (1982) model assumes that events with long durations initiate major metrical units, because they are perceptually more salient than short durations. Thus, longer durations tend to be assigned higher metrical levels (larger periods between accents) than short durations. Corresponding perceptual cues have been documented for nonmusical rhythms (Woodrow, 1951); events that are louder or of longer duration than their neighbors are perceived as accented. Thus, the correct metrical grouping may be found by weighting each musical event in a given sequence according to perceived cues to accentuation. In performance, an intended metrical interpretation may be communicated by marking the primary accents, most often through variations in intensity or duration (Palmer, 1989; Shaffer, Clarke, & Todd, 1985; Sloboda, 1983). However, duration and intensity cues are influenced in both composition and performance by many factors in addition to meter (Nakamura, 1987; Palmer, 1988; Shaffer & Todd, 1987). Often these cues are ambiguous, interactive, or simply absent; yet the listener still determines the meter correctly. Therefore, it is unlikely that sensory cues alone determine the meter.

Some coding models of serial behavior suggest that multiple temporal periodicities are perceived in rhythmic patterns (Garner, 1974; Royer & Garner, 1966). Coding models propose that the perceptual organization of serially ordered events is ruled by coding principles that determine the perceptual dominance of a particular alternative (Garner, 1974; Royer & Garner, 1966; Vos, 1977). Typically, Gestalt principles of perceptual organization interact with patterns of presentation rate and event structure (Garner, 1974), and patterns tend to be perceived according to the more economical code. For instance, Povel's (1981) model of musical rhythm consists of coding principles defining temporal nesting. Preferred (good) codings are simple codings, based on Fraisse's (1956) finding that rhythms with durations in a ratio of 2:1 are simplest. Povel's model reflects an equal number of subdivisions throughout the pattern in a hierarchical grid, with binary (1:1) or 2:1 subdivisions at each level. Povel (1981; Povel & Essens, 1985) extended this coding model to explain rhythmic complexity judgments and reproductions of temporal sequences. In a dynamic transformation approach, the perception of good or poor rhythms is attributed to multiple temporal periodicities associated with different transformations of the same temporal pattern (Jones, 1976). Thus, these models of serial patterning attach importance to the simultaneous perception of multiple temporal periodicities.

Another proposed perceptual cue to meter is repetition, assuming that a repeated pattern will occur in the same metric position (within a bar) on its different repetitions. Steedman's (1977) model of meter perception bases metrical inferences on the repetitions of melodic fragments. Similarly, rhythmic repetition, or the recurrence of a given rhythmic pattern, is an important cue in a music-theoretic account of meter (Lerdahl & Jackendoff, 1983). Transposed pitch patterns can signal meter as well, through the temporal locations of the transpositions (Longuet-Higgins & Lee, 1982; Steedman, 1977). However, few musical forms contain sufficient melodic or rhythmic repetitions to allow perception of meter from this cue alone.

One commonality of the music-theoretic and psychological notions outlined previously is that the listener's sense of meter arises from an interaction between abstract, context-free knowledge of meter and context-dependent knowledge from specific musical events. Thus, a specific pattern of musical events may be interpreted as containing different accent combinations if considered in different metrical contexts. This article addresses the abstract knowledge of meter that affects perceptual organization of specific musical experiences. In the studies described later, we consider the kinds of knowledge that musically trained and untrained listeners may have about metrical structure, how this knowledge may resemble statistical regularities in Western tonal music, and the consequences for perceptual organization and memory of specific musical experiences.

Frequency Distributions

It has long been accepted that musical styles contain statistical regularities in various musical dimensions, such as pitch, duration, and intensity (Meyer, 1956; Pinkerton, 1956; Youngblood, 1958). Through experience, listeners may internalize musical relationships reflected by these statistical regularities and apply this knowledge to recognize music in that style. For instance, chord progression and melodic contour regularities in Western tonal music provide redundancy, which aids melody recognition (Cohen, Trehub, & Thorpe, 1989). Statistical regularities in musical composition may provide a rich source of information on mental representations for meter. If mental representations are likely to include regularities in familiar musical styles, then the temporal regularities in musical compositions may provide insights into the perceptual organization of meter.

Statistical analyses of music from diverse sources including information theory, artificial intelligence, and music theory have addressed questions such as what distinguishes different musical styles or composers or how to compose a piece of a particular musical period (Cohen, 1962; Pinkerton, 1956; Youngblood, 1958). Although most studies investigate these questions relative to tonality (Knopoff & Hutchinson, 1983; Pinkerton, 1956; Youngblood, 1958), a few have addressed the temporal regularities in music. In a statistical analysis of durations in a sample of Western tonal music, Fraisse (1982) reported that 80% of musical events were based on two durations, in a ratio of 2:1. This suggests few temporal periodicities or a metrical hierarchy with correspondingly few levels if duration is the only cue to meter available. Another analysis of durations in Western music suggested a small temporal alphabet of clusterings of repetitions, lengthenings, and shortenings of successive durations (Hutchinson & Knopoff, 1987). None of these analyses, however, addressed the relation of the statistical regularities to meter.

The frequency with which musical events in a piece occur in a given metrical context may provide important perceptual cues to meter. For any metrical level (or temporal periodicity between events with the same accent strength) to be instantiated in a musical composition, it is necessary that a sufficient number of successive (adjacent) beats be sounded at each level. Therefore, composers may reinforce the meter by manipulating the frequency of events at each metrical level, allowing listeners to differentiate meters on the basis of the relative frequencies of events' temporal locations.

To investigate this hypothesis, we examined musical excerpts for the frequency of occurrence of events in each temporal location. We chose musical excerpts from four composers of Western tonal music, representing a range of musical styles. If frequency of occurrence is an important cue to meter, then frequency distributions of musical events in different temporal locations should differentiate one meter from another, both within and across musical periods. Alternatively, if period or style of music, rather than meter, determines event distributions in musical compositions, then we should fail to see consistencies across the four different compositional styles.

We also investigated the correspondence between frequency distributions of musical events and the music-theoretic notions of meter discussed earlier (Lerdahl & Jackendoff, 1983). This theory is appropriate for comparison with the present study because it describes a listener's perception of rhythmic, metric, harmonic, and melodic organization. One component of the music theory, metrical structure, predicts metrical accent strength in terms of a periodic hierarchy of strong and weak beats, indicated by the dashed line in Figure 1. Each musical event in a piece is aligned with a metrical grid, which expresses the regular alternation of strong and weak beats at different hierarchical levels. This predicted accent strength may be reflected in the frequency with which events are sounded at each temporal location. To test this hypothesis, the music-theoretic predictions in Figure 1 will be compared with the frequency distributions for each meter.

Method

Materials. The following four composers and their piano compositions were chosen for analysis: J. S. Bach, French Suites III (Allemande and Sarabande), IV (Gigue), and VI (Gavotte); Mozart, Piano Sonatas K310, 311, 545, and 576; Brahms, Piano Intermezzi Opus 118, No. 1, and 119, Nos. 2, 3, and 4; and Shostakovich, Piano Prelude III and Fugues III, VI, and XI. Each of these choices contained pieces written in each of the following four meters: $\frac{2}{4}$, $\frac{3}{4}$, $\frac{4}{4}$, and $\frac{6}{8}$ (with primary accents every two, three, four, or six beats, respectively). Thus, the selections contained one piece representing each compositional style and each meter. Because the musical pieces differed in length and density (or number of simultaneous parts or voices), the analysis included only the first musical section (approximately the first 20 bars) of the melody or primary part (in the case of fugues, the subject was included).

Procedure

The frequencies with which note events occurred in each temporal location were calculated for each musical excerpt. Locations were defined in terms of the smallest subdivision of durations present in a bar. Thus, for music based on $\frac{4}{4}$ meter (with every fourth quarter note accented) with smallest durations of 16th notes, each bar contained 16 equal subdivisions or event locations. The counts were computed by calculating each time a note event began in Location 1, Location 2, and so on. For the excerpts chosen, there were 16 temporal locations within each bar for the pieces in $\frac{2}{4}$ (each location = one 32nd note) and $\frac{4}{4}$ (each location = one 16th note) meters, and 12 locations within each bar for the $\frac{3}{4}$ and $\frac{6}{8}$ meters (each location = one 16th note). Rests (during which no event was sounded) and notes marked as tied or held over from a previous event were not included in the analysis.

Results

First, the agreement across compositional styles was analyzed by correlating the frequency distributions within each meter. Table 1 shows the intercomposer correlations for musical compositions in each of the four meters. With the exception of one piece, each of the intercomposer correlations is significant, indicating that frequency distributions within meter are consistent across these four musical composers. The

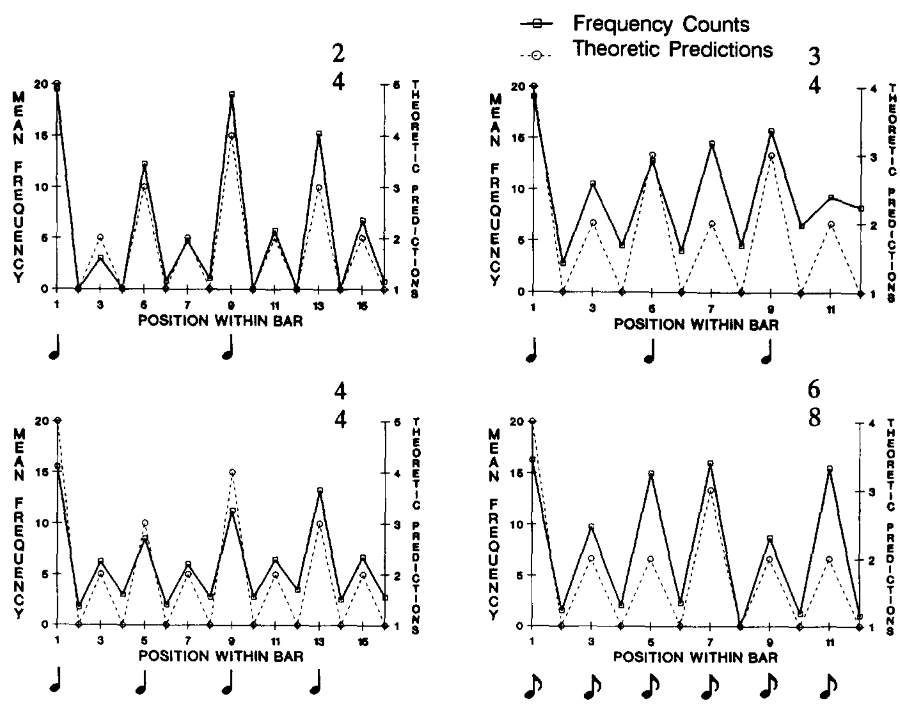

Figure 1. Mean frequency of occurrence distributions of musical events (solid line) and theoretic predictions (dashed line) by meter.

Table 1
Intercorrelations Among Frequency Distributions by Meter

Meter	Composer	Bach	Mozart	Brahms	Shostakovich
$\frac{2}{4}$	Bach	—			
	Mozart	.96**	—		
	Brahms	.873**	.902**	—	
	Shostakovich	.925**	.945**	.822**	—
$\frac{3}{4}$	Bach	—			
	Mozart	.819**	—		
	Brahms	.684**	.468*	—	
	Shostakovich	.687**	.81**	.677**	—
$\frac{4}{4}$	Bach	—			
	Mozart	.357	—		
	Brahms	.361	.89**	—	
	Shostakovich	.218	.874**	.949**	—
$\frac{6}{8}$	Bach	—			
	Mozart	.927**	—		
	Brahms	.976**	.968**	—	
	Shostakovich	.97**	.954**	.967**	—

Note. $n(\frac{2}{4}, \frac{4}{4}) = 16$; $n(\frac{3}{4}, \frac{6}{8}) = 12$.
* $p < .10$. ** $p < .05$.

exception, music by Bach in $\frac{4}{4}$ meter, contains a melody based on repeating 16th notes, and thus showed little variation in event frequency across temporal locations. Given the otherwise high degree of consistency, subsequent analyses were performed on the average frequency distribution for each meter.

Figure 1 shows the average frequency distributions by temporal location for each meter. The differences across temporal locations correspond to the predictions from music-theoretic notions of accent strength (Lerdahl & Jackendoff, 1983), also shown in Figure 1. Thus, the event predicted to be most highly accented (in Location 1, the first beat of a bar) was also the most frequent event location. To test this correspondence, the frequency distributions were correlated with the music-theoretic predictions within meter. Each correlation was highly significant ($\frac{2}{4}$, $r = .98$; $\frac{3}{4}$, $r = .92$; $\frac{4}{4}$, $r = .96$; $\frac{6}{8}$, $r = .87$), indicating that predicted accent strength corresponds with frequency of occurrence in these musical excerpts. Figure 1 also indicates that events preceding theoretically strong locations were slightly more frequent than events following strong locations (for instance, events were more common in Location 13 than in Location 5 in $\frac{2}{4}$ meter). This may reflect a compositional technique by which metrically important events are cued by preceding events.

To further analyze differences in metrical accent strength across temporal locations, a Fourier analysis was performed on the average frequency distributions. A Fourier analysis is a spectral analysis of the different frequencies or periodicities present in a nonperiodic signal such as these counts (Jenkins & Watts, 1968). In this application, the periodicities correspond to temporal distances between events with equivalent accent strength or to different hierarchical levels in the musical meter. The Fourier analysis addresses two questions: Are there periodic components in the distributions, and do pieces composed in different meters have the same periodicities (and corresponding hierarchical levels)?

The strength of each periodicity was calculated for each meter, represented by the percentage of the overall mean square variance accounted for by that periodicity. For the $\frac{2}{4}$ meter, the periodicities of every two (58%) and four (35%) temporal subdivisions (corresponding to each eighth and quarter note in a measure) were strongest. For the $\frac{3}{4}$ meter, the periodicities of every two (72%) and four (11%) subdivisions (corresponding to each eighth and quarter note) were strongest. For $\frac{4}{4}$ meter, the periodicities of every two (65%) and four (25%) subdivisions were strongest (corresponding to each eighth and quarter note). Finally, for $\frac{6}{8}$ meter, the periodicities of every two (88%) and six (6%) subdivisions (corresponding to each eighth and dotted quarter note) were strongest. The phase of each periodicity was equal to or close to zero, relative to the first beat of the bar (temporal location 1 in Figure 1). Figure 1 indicates higher frequency of events congruent with these periodicities. Thus, the Fourier analysis indicates strong periodic components in the frequency distributions for each meter corresponding to hierarchical levels of metrical accent proposed by Lerdahl and Jackendoff (1983).

Discussion

The present findings suggest that frequency distributions of musical events in different metrical locations provide a robust cue to meter. The same statistical regularities were found in a range of compositional styles despite the variety of implementations of harmony, rhythmic variation, and melodic importance. This finding argues that frequency distributions of musical events are primarily influenced by meter rather than by musical style or period. Also, the relative weighting of temporal periodicities differed across meter, as evidenced in the Fourier analyses. Finally, the frequency distributions were congruent with music-theoretic predictions of accent placement for each of the four meters (Lerdahl & Jackendoff, 1983), suggesting that metrical accent may be instantiated through frequency of occurrence information.

There are several reasons why frequency distributions may be a useful metrical cue for listeners. One reason is that the information is robust across performance changes in other musical variables such as loudness, another proposed cue to meter perception. Another reason is that frequency distributions are established early in the music (as early as the first 20 bars, upon which these frequency counts were based), and therefore may aid meter perception relatively quickly, corresponding to reports of listeners' early establishment of a sense of meter (Longuet-Higgins & Lee, 1982). Finally, the statistical regularities appear to be preserved from one compositional style to another, indicating that the same abstract knowledge may apply to a wide variety of music. Although the distributions reported here survey only a small sample of compositional styles and pieces, the high degree of conformity indicates that a hierarchical representation of meter is reinforced in musical composition, and may serve to instantiate specific meters for a listener.

There are compositional benefits of stable frequency distributions for meter as well. If meter is signaled through the frequencies with which events occur at different locations, then musical compositions may contain multileveled metrical distributions to ensure or discourage perception of meter. The degree to which metrical frameworks are instantiated, under the composer's control, may account for metrical ambiguity. Strong statistical regularities for meter may allow emphasis of other musical dimensions such as pitch or intensity by reducing the attention listeners must allocate to meter and increasing listeners' anticipations for certain event locations.

Although the frequency distributions described here appear quite stable, we do not yet know if perception of meter reflects these statistical properties. It is possible that these compositional regularities do not represent the mental framework of listeners, who must often disambiguate more complex forms of meter than those described here. Alternatively, the frequency distributions may provide the kind of abstract probabilistic framework necessary for listeners to perceive meter under ambiguous or noisy circumstances. The next section investigates the types of mental structures for meter that are evoked in perception of simple temporal sequences (ones in which the compositional cues of frequency distribution are not available). Our aim is to determine whether or not impoverished temporal contexts evoke hierarchically structured knowledge about metrical structure, even when this structure is not contained in the sensory context.

Perceptual Hierarchies

Perceptual hierarchies for some musical dimensions, such as tonality, have been extensively documented. These hierarchies incorporate listeners' abstract knowledge of musical structure in the perceptual organization of tones, chords, and keys (Bharucha & Krumhansl, 1983; Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979). In these experiments, listeners provided goodness-of-fit judgments for musical events present in a tonal context. The judgments reflected abstract knowledge of tonal relationships that were not presented in the sounded patterns and, therefore, must have been implicit in the listeners' perceptual organization. Furthermore, the judgments revealed hierarchical relationships among individual notes, chords, and keys found in music-theoretic descriptions, even though the listeners did not have explicit knowledge of music theory (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979).

We describe a similar approach to studying the role of implicit knowledge for meter by collecting goodness-of-fit judgments for single events presented in a metrical context. If listeners' knowledge of meter underlies the perception of temporal sequences, then the goodness-of-fit judgments should change with different metrical contexts. Furthermore, the implicit knowledge may reflect the frequency distributions and music-theoretic predictions of accent placement described previously.

Three questions were addressed in a study of abstract knowledge of meter: First, does listeners' implicit knowledge (beyond that of the immediate sensory context) contribute to perception of temporal sequences? Second, do listeners represent meter with many or few hierarchical levels? And finally, what role does musical experience play in mental representations for meter? To address these questions, listeners were asked to rate how well single temporal events fit in a given metrical context, for a set of different temporal locations and metrical contexts. The metrical contexts (a repeating beat) were designed to provide as little sensory information about metrical accent as possible. Finally, the judgments of musically trained and untrained listeners were compared to address the effects of musical experience.

Method

Subjects. Twenty listeners from the Ithaca, New York, community participated in the study. Ten of the listeners had at least five years of formal instruction on a musical instrument (mean: 7.4 years), and 10 had less than two years of training on any instrument. None of the listeners had hearing problems, and only 2 musicians had more than one semester of training in music theory.

Materials. The temporal sequences, illustrated in Figure 2A, were constructed as follows: Each sequence consisted of a metrical context, defined by a series of nine low-pitched beats, called *context beats,* which represented the first event in each measure. Because tempo affects perception of meter in polyrhythms (Handel & Lawson, 1983), we attempted to simulate common tempos (rates of presentation) for each meter by defining durations between context beats based on Vos's (1976) reports of the average duration of meters in a variety of piano performances. The duration between context beats for $\frac{2}{4}$, $\frac{3}{4}$, $\frac{4}{4}$, and $\frac{6}{8}$ metrical contexts were 1,744 ms, 2,400 ms, 3,488 ms, and 4,800 ms, respectively. After four repetitions of the context beat, a higher pitched probe beat was sounded between the remaining five context beats (also shown in Figure 2A). Each of the four probe beat locations remained the same relative to the context beats within a trial; for each trial, the locations were one of 16 equal divisions of the context for $\frac{2}{4}$ and $\frac{4}{4}$ meters and one of 12 equal divisions of the context for $\frac{3}{4}$ and $\frac{6}{8}$ meters. The number of possible locations was determined by repeating binary subdivisions for each metrical context, analogous to the division of durations in musical meters. Thus, the durations between possible probe beat locations were 109 ms in $\frac{2}{4}$, 200 ms in $\frac{3}{4}$, 218 ms in $\frac{4}{4}$, and 400 ms in $\frac{6}{8}$ metrical context.

Apparatus. The temporal sequences were produced by a DMX-1000 signal-processing system under the control of a PDP-11/23+ computer. Sound was played over an NAD stereo amplifier through a Mission Electronic loudspeaker set directly in front of the listener. The timbre, a short percussion sound, was characterized by a high-frequency noise burst and an amplitude envelope with a short attack (less than 10 ms) decaying linearly over the duration of the tone, which was 35 ms. The probe beat was defined as twice the frequency of the context beat, creating two distinguishable sounds.

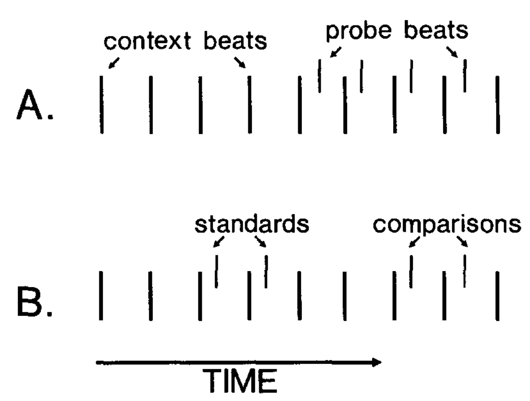

Figure 2. Example of temporal sequences used as stimulus materials for goodness-of-fit ratings (A) and discrimination ratings (B).

Procedure. Listeners heard a temporal sequence on each trial. Trials began with a low-pitched beat, defined as a context beat. Listeners were asked to think of each context beat as the first of N beats, where $N = 2$, 3, 4, or 6. (These instructions of metrical context corresponded to the durations of 1,744 ms, 2,400 ms, 3,488 ms, or 4,800 ms between context beats, respectively.) After 4 repetitions of the context beat, listeners were told that a higher pitched beat would enter, somewhere between the context beats. Listeners rated "how well the high-pitched beats fit with the context beats" on a 7-point scale where 1 = *a poor fit* and 7 = *a good fit.* After an 8-s response period, the next trial began.

Judgments were made for each of the 4 metrical contexts and for each probe beat position, with 2 repetitions per trial type; there were 16 probe beat positions for $\frac{2}{4}$ and $\frac{4}{4}$ contexts, and 12 probe beat positions for $\frac{3}{4}$ and $\frac{6}{8}$ contexts, giving a total of 112 trials. Trials were blocked by metrical context, and randomly ordered within block; listeners heard all trials with the 2-beat context together, and so on. Presentation order of metrical contexts was counterbalanced across subjects in a Latin-square design. Listeners heard 5 practice trials before the start of each block. The experiment lasted approximately 2 hours run over a period of 2 days, and listeners were paid $8 for their participation.

Results

The mean ratings for each metrical context are shown in Figure 3 for musically trained and untrained listeners. Because there were no effects of counterbalance order, results were combined across this variable. An analysis of variance (ANOVA) was performed on the ratings for each metrical context by probe beat position (12 or 16) and musical training (high/low). There was a significant effect of probe beat position for each of the four metrical contexts ($p < .01$ in each analysis). The rating profiles in Figure 3 indicate a hierarchy or graded ordering for each meter, with the highest rating generally given to the probe beat coinciding with the context beat. There was also a significant interaction of musical training with probe beat position in all meters except $\frac{6}{8}$ ($p < .05$ in each of the three analyses), indicating that musical experience influenced the ratings given to different probe beat positions. As seen in Figure 3, musicians' ratings showed a larger range and more variation than nonmusicians' ratings.

To analyze further the interaction between musical training and probe beat position, a Fourier analysis was performed on the ratings. The Fourier analysis addressed whether there are periodic components in the ratings, and whether the same periodicities (and corresponding hierarchical levels) were strongest for the two listener groups. Figure 4 shows the relative strengths of the periodicities in the ratings of each listener group for each metrical context. Strength is represented by the percentage of the mean square variance in the ratings accounted for by each periodicity. The periodicities

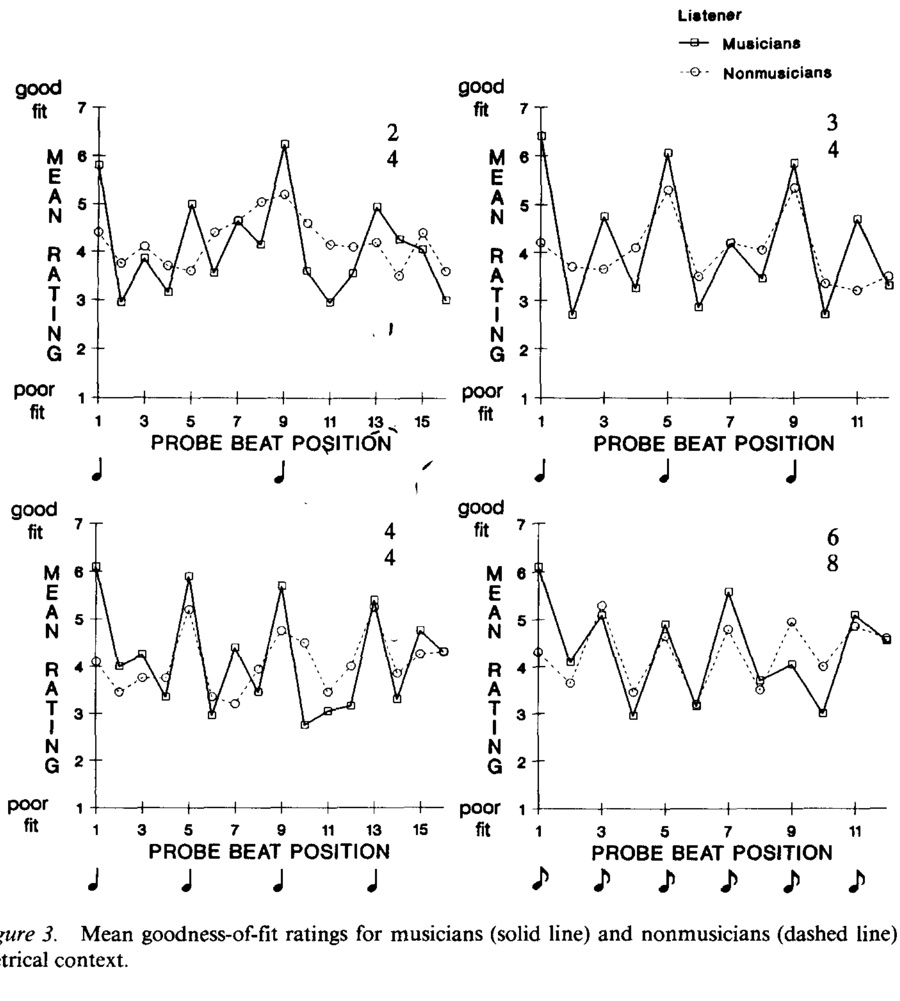

Figure 3. Mean goodness-of-fit ratings for musicians (solid line) and nonmusicians (dashed line) by metrical context.

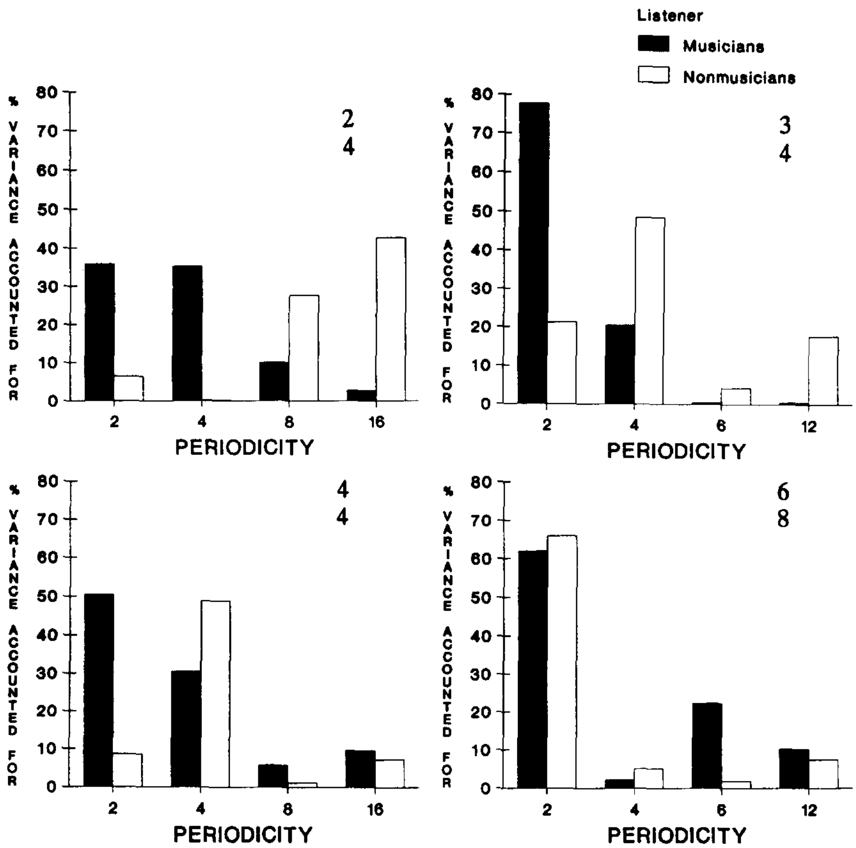

Figure 4. Relative strength of periodicities in goodness-of-fit ratings for musicians (solid bars) and nonmusicians (empty bars) by metrical context.

correspond to the grouping of events into different hierarchical levels in the musical meter.

The two listener groups emphasized different temporal periodicities. In the $\frac{2}{4}$ meter, musicians' ratings showed strongest periodicities every two and four temporal subdivisions (corresponding to each eighth and quarter note in the bar). In contrast, nonmusicians showed strongest periodicities every 16 and 8 subdivisions (corresponding to the beginning and midpoint of a musical bar). Both listener groups showed the same strongest periodicities in the $\frac{3}{4}$ meter (every 2 and 4 subdivisions), with the smaller periodicity stronger in the musicians' ratings and the larger periodicity stronger in the nonmusicians' ratings. In the $\frac{4}{4}$ and $\frac{6}{8}$ meters, the musicians' ratings showed stronger periodicities aligned with equal beat divisions than those of nonmusicians, and the first periodicities explained a larger percentage of the variance for musicians than for nonmusicians. Overall, more variance was accounted for by smaller periodicities in the musicians' ratings, indicating perceptual organization of the temporal patterns above and beyond the levels suggested by the instructions. The nonmusicians' ratings reflected only periodicities coincident with the beats they were instructed to imagine.

Finally, the goodness-of-fit judgments were compared with the music-theoretic predictions and the frequency distributions described previously. The musicians' goodness-of-fit judgments were included because of the finer differentiation in their ratings indicated by Figure 3. Table 2 contains the correlations of their ratings with the musical and psychological measures. The goodness-of-fit judgments correlated significantly with the music-theoretic predictions and the frequency distributions for each of the four meters ($p < .05$), indicating excellent agreement between theoretical, compositional, and perceptual notions of metrical accent placement.

Discussion

Listeners' goodness-of-fit judgments of events in temporal sequences reflect knowledge of metrical accent structure. The judgments demonstrated a graded ordering of events in different temporal locations, dependent on the suggested metrical context. There were no stimulus cues that differentiated between the temporal locations. Instead, listeners' mental representations for meter, instantiated by the suggested metrical context, contributed to the hierarchical ratings, with musicians demonstrating knowledge of hierarchical levels beyond those suggested by the metrical context. It is unlikely that this knowledge was simply due to formal training (only 2 of the musicians in this study had significant exposure to music theory). These results suggest that abstract knowledge of meter affects perception of temporal patterns, analogous to previous findings with a similar paradigm, of abstract knowl-

Table 2
Musical and Psychological Correlations by Metrical Context

Meter	Variable	Theory	Counts	Fit	Memory
$\frac{2}{4}$	Music theory	—			
	Frequency counts	.976**	—		
	Goodness of fit	.848**	.861**	—	
	Memory residuals	.316*	.335*	.339*	—
$\frac{3}{4}$	Music theory	—			
	Frequency counts	.922**	—		
	Goodness of fit	.967**	.889**	—	
	Memory residuals	.565**	.546**	.565**	—
$\frac{4}{4}$	Music theory	—			
	Frequency counts	.961**	—		
	Goodness of fit	.864**	.838**	—	
	Memory residuals	.545**	.433**	.532**	—
$\frac{6}{8}$	Music theory	—			
	Frequency counts	.871**	—		
	Goodness of fit	.854**	.836**	—	
	Memory residuals	.384*	.319	.431**	—

Note. $n(\frac{2}{4}, \frac{4}{4}) = 16$; $n(\frac{3}{4}, \frac{6}{8}) = 12$.
Memory residuals: $n(\frac{2}{4}, \frac{4}{4}) = 32$; $n(\frac{3}{4}, \frac{6}{8}) = 24$.
* $p < .10$. ** $p < .05$.

edge affecting perception of tonality (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979).

Listeners' judgments reflected multiple temporal periodicities of perceived accent in the same pattern. The same periodicities were emphasized in the frequency distributions of events in musical compositions, with strongest accents at the beginning of the bar, and finer differentiation of small periodicities. These findings suggest that listeners, like composers, have abstract knowledge of multileveled metrical hierarchies in musical composition. This abstract knowledge contributes to perceptual organization of rhythm by interacting with sensory information, recoding impoverished temporal sequences such as these into structures of rich interconnections. Although the present experiment incorporated only one rate of presentation for each metrical context, the high correspondence of listeners' judgments with both frequency distributions from musical compositions and music-theoretic predictions of accent placement (in which rate does not matter) suggest that listeners' knowledge of metrical accent placement is influenced by relative rather than absolute duration patterns.

Musical training enriches mental representations for meter, with finer differentiation between hierarchical levels and greater emphasis on smaller periodicities. This conclusion was supported by greater variation in musicians' than in nonmusicians' ratings and by the Fourier analyses indicating greater weighting of smaller periodicities. The metrical structures exhibited by all listeners fit the same basic framework, with experienced listeners demonstrating finer differentiation in levels of accent. This finding suggests that, as experience is gained, mental representations for meter become richer, and more closely resemble the relative weights of hierarchical levels seen in frequency distributions in Western tonal music and music-theoretic predictions of accent placement (Lerdahl & Jackendoff, 1983).

Memory Confusions

How does abstract knowledge of meter affect memory for temporal information in auditory sequences? Previous work indicates that rhythmic sequences fitting a metrical hierarchy are more easily discriminated from other rhythmic sequences than those that do not fit a metrical hierarchy (Bharucha & Pryor, 1986) and are more accurately imitated during reproduction than are nonmetrical sequences (Povel, 1981). Metrical structure also affects the processing of other musical dimensions; pitch events at metrically weak locations tend to be confused or less well-remembered than events at metrically strong locations (Jones, 1976; Jones, Boltz, & Kidd, 1982). In a similar finding, memory for pitch sequences was dependent on the perceived temporal frame, such that temporal structures that coincided with pitch structures enhanced recall, whereas temporal structures that conflicted with pitch structures negatively affected recall (Deutsch, 1980). If metrical structure mediates memory for temporal sequences, as these findings suggest, then the likelihood of memory confusions should correspond to the number of hierarchical levels reflecting accent strength. Specifically, the likelihood of memory errors at each temporal location should be inversely correlated with accent strength, predicted by the number of metrical levels predicted for each location.

To test this hypothesis, a temporal discrimination task was designed using the same metrical contexts (a repeating beat) as in the previous study. In this task, listeners hear two temporal patterns and are asked to judge whether or not they are the same. The accuracy of the ratings should indicate memory confusions inversely correlated with the predicted accent structure for the suggested metrical context. Thus, for a given metrical context, there should be fewer confusions for events occurring in strong (accented) metrical locations and more confusions for events in weak (unaccented) metrical locations. Because the previous study indicated greater differentiation among metrical levels with more musical experience, only musically experienced listeners were included in this study.

Method

Subjects. Sixteen listeners from the Ithaca, New York, community participated in the study. Each of the listeners had at least five years of formal instruction on a musical instrument (mean: 7.9 years), and an average of 12 years experience playing that instrument. None of the listeners had any hearing problems, and only 3 had more than one semester of training in music theory.

Materials. The temporal sequences, exemplified in Figure 2B, were constructed similar to the stimuli in the previous experiment. Each temporal sequence consisted of a metrical context, defined by a series of nine low-pitched beats (context beats), based on the following intercontext beat intervals: 1,744 ms, 2,400 ms, 3,488 ms, or 4,800 ms, simulating the meters $\frac{2}{4}$, $\frac{3}{4}$, $\frac{4}{4}$, and $\frac{6}{8}$, respectively. After two repetitions of the context beat, a higher pitched probe beat, the standard, was sounded between the next two context beats. The context and standard were each sounded twice (in the same relative positions), then the standard disappeared, and the context beat was sounded alone twice more. Then the higher pitched probe beat returned, the comparison, in either the same or different temporal position as the standard. The comparison and context beat were each sounded twice more (in the same relative positions); then the context beat was sounded once more, ending the trial. The standards occurred in the same positions as in the previous experiment; the positions were 1 of 16 equal divisions of the context for $\frac{2}{4}$ and $\frac{4}{4}$ meters and one of 12 equal divisions of the context for $\frac{3}{4}$ and $\frac{6}{8}$ meters. The comparisons occurred in positions either immediately before, immediately after, or the same as, the standard. The listeners' task was to judge whether or not the standard and the comparison occurred in the same temporal position.

Apparatus. The temporal sequences were produced by Yamaha TX816 tone generators, operating on FM principles of sound synthesis. Sound was passed from a Yamaha mixer and amplifier to a JBL speaker set directly in front of the listener. The timbre, a short percussion sound, was characterized by an amplitude envelope with a short attack (less than 10 ms) decaying linearly over the duration of the tone, which was 35 ms.

Procedure. Listeners heard a temporal sequence on each trial. Listeners were told they would hear a low-pitched beat, called a context beat. They should think of each context beat as the first of N beats, where $N = 2, 3, 4$, or 6 (representing the musical meters $\frac{2}{4}$, $\frac{3}{4}$, $\frac{4}{4}$, or $\frac{6}{8}$). After 2 repetitions of this context beat, a higher pitched beat would enter, located between the context beats. After 2 repetitions, the high-pitched beat would disappear, leaving only the context beat. Then, the high-pitched beat would reappear for 2 repetitions. The listeners' task was to rate whether or not the return of the high-pitched beat occurred in the same position as its first sounding, relative to the context beats. Listeners made the ratings on a 6-point scale where 1 = *very sure same* and 6 = *very sure different.*

Judgments were made for each of the 4 metrical contexts, each standard position, and each of 3 possible comparison positions (before, same as, or after standard), giving a total of 168 trials. Trials were blocked by metrical context, and trials were randomly ordered within blocks; listeners heard all trials with the 2-beat context together, and so on. Presentation order of blocks was counterbalanced across subjects in a Latin-square design. Listeners heard 5 practice trials before each block. The experiment lasted approximately 2 hours, run over a 2-day period, and listeners were paid $8 for their participation. All other procedures were identical to those in the previous experiment.

Results

Because there were no effects of counterbalance order, the ratings were combined across this variable. ANOVAs were performed on average ratings within each metrical context by standard position (12 or 16) and comparison position (before, same, or after standard). There was a significant interaction of standard and comparison positions within each of the four meters ($p < .05$ for each metrical context), and the ratings were analyzed separately for trials in which the standard and comparison were in the same or different positions. ANOVAs on the mean ratings for trials on which standard and comparison were in the same location (hereinafter referred to as *same trials*) indicated a significant main effect of standard position for each meter ($p < .05$ for each metrical context). The same analysis of ratings for trials on which standard and comparison were in different locations (hereinafter referred to as *different trials*) yielded a significant main effect of standard position for each meter ($p < .05$ for each metrical context), indicating that the likelihood of detecting the difference between standard and comparison differed with metrical location. The main effect of comparison location (before vs. after) was just significant for the $\frac{3}{4}$ and $\frac{4}{4}$ metrical contexts ($p < .05$).

To address whether or not an identical metrical accent structure affects both the same and different trials for a given standard position, a measure of accuracy for each standard position was calculated from the difference between mean ratings for same and different trials (different minus same). The differences were calculated both for the trials on which the comparison was before or after the standard. This difference represents an accuracy score, or the ability to distinguish a comparison in the same position as the standard from one that is in a different position. A perfect accuracy score for each metrical location would be 5 (a rating of 6 or *different* minus a rating of 1 or *same*).

The accuracy scores suggested a serial distance effect within the metrical context, such that events closest to the context beats (such as Positions 1, 2, or 16 in $\frac{2}{4}$ metrical context) are most well discriminated, while events farthest from the context beats (such as Position 9) are least well discriminated. To test whether serial distance affected accuracy of responses, a variable was created to code serial distance from the closest context beat. Thus, for $\frac{2}{4}$ metrical context, Position 1 in Figure 3 was coded 0; Positions 2 and 16 were coded 1; Positions 3 and 15 were coded 2, and so on. The (negative) correlation between serial distance from context beats and accuracy scores was strong for 3 of the 4 metrical contexts ($\frac{2}{4}$, $r = -.76$, $p < .01$; $\frac{3}{4}$, $r = -.62$, $p < .01$; $\frac{4}{4}$, $r = -.67$, $p < .01$; $\frac{6}{8}$, $r = -.36$, $p < .10$). This correspondence indicates that events farthest from the context beats were more likely to be confused as the same (when they were in fact different) or more likely to be confused as different (when they were in fact the same). The context beats may have served in this task as perceptual markers from which temporal locations were judged.

To investigate whether representations of metrical accent affected discrimination judgments above and beyond serial distance from context beats, the serial distance effects were removed from the accuracy scores. Residual scores were calculated by subtracting the accuracy ratings predicted from a linear regression fit of serial distance from the observed accuracy scores. The mean residuals for each standard position, shown in Figure 5, reflect a multileveled hierarchy of accent strength affecting memory confusions. ANOVAs on the residuals for each metrical context indicated a significant effect of standard position ($p < .05$ for each metrical context). Thus, the discrimination judgments were influenced by both serial distance from context beats and by perceived accent strength of temporal location within metrical context.

To analyze further the differences between standard positions, a Fourier analysis was performed on the memory residuals. The strength of each periodicity was calculated for each meter, represented by the percentage of the overall mean square variance accounted for by that periodicity. For the $\frac{2}{4}$ meter, the periodicities of every 4 (22%) and 8 (29%) temporal subdivisions (corresponding to each quarter and half note in a measure) were strongest. For the $\frac{3}{4}$ meter, the periodicities of every 2 (44%) and 6 (22%) subdivisions (corresponding to each eighth note and dotted quarter note) were strongest. For $\frac{4}{4}$ meter, the periodicities of every 2 (19%), 4 (19%), and 8

(23%) subdivisions were strongest (corresponding to each eighth, quarter, and half note). Finally, for $\frac{6}{8}$ meter, the periodicities of every 2 (14%), 6 (29%), and 12 (37%) subdivisions (corresponding to each eighth note, dotted quarter note, and whole note) were strongest. The phase of each periodicity was equal or close to zero relative to the first beat of the bar (temporal position 1 in Figure 5). Figure 5 shows higher ratings of events congruent with these periodicities, indicating that discrimination judgments were more accurate for events in metrically strong than metrically weak locations. The strength of small periodicities represents contributions of abstract metrical knowledge beyond the information given in the instructions.

Finally, the memory residuals (accuracy scores with serial distance effects removed) were compared with the other musical and psychological variables (Table 2). The memory residuals correlated significantly with the music-theoretic predictions, the frequency distributions, and the goodness-of-fit judgments, in 8 of 12 instances ($p < .05$). Memory residuals for the $\frac{6}{8}$ context were slightly less consistent with the other variables, possibly because of the worse fit of serial distance from context beat (effects removed from the accuracy scores). However, 3 of the remaining 4 correlations approached significance ($p < .10$), indicating high agreement among theoretical, compositional, perceptual, and memory measures of metrical accent structure.

Discussion

Memory confusions from a discrimination task indicated that abstract knowledge of meter affects encoding and retrieval of temporal sequences. Events occurring in metrically strong locations were more easily recognized and less likely to be confused with events occurring in neighboring temporal locations. Furthermore, memory strength corresponded with music-theoretic predictions, frequency distributions in musical compositions, and goodness-of-fit judgments for similar temporal sequences. These findings emphasize the robustness of mental representations for meter, in which abstract accent structures reflect perceived stability and memory strength.

Serial distance effects also affected memory for temporal sequences. Because temporal patterns unfold over time, the present task required memory of relative durations over a time span of several seconds. In the previous study, the attentional demands were not as great; goodness-of-fit ratings could have been based solely on a single presentation of a probe beat, a duration spanning less than 1 s. After the serial position effects were removed, however, there was still an effect of metrical accent structure, indicating that hierarchical representations for meter operated in addition to serial distance.

These findings indicate that memory for temporal sequences is dependent on the inferred metrical framework, such that temporal sequences coinciding with accented positions benefit from enhanced recall, while events coinciding with unaccented positions do not benefit. A multileveled metrical hierarchy mediates discrimination of temporal patterns, with accent strength inversely correlated with likelihood of memory errors. The instantiation of a metrical context may facilitate memory by increasing associations among events in each hierarchical level, allowing rich interconnections to aid discrimination of these impoverished sequences as well as complex music.

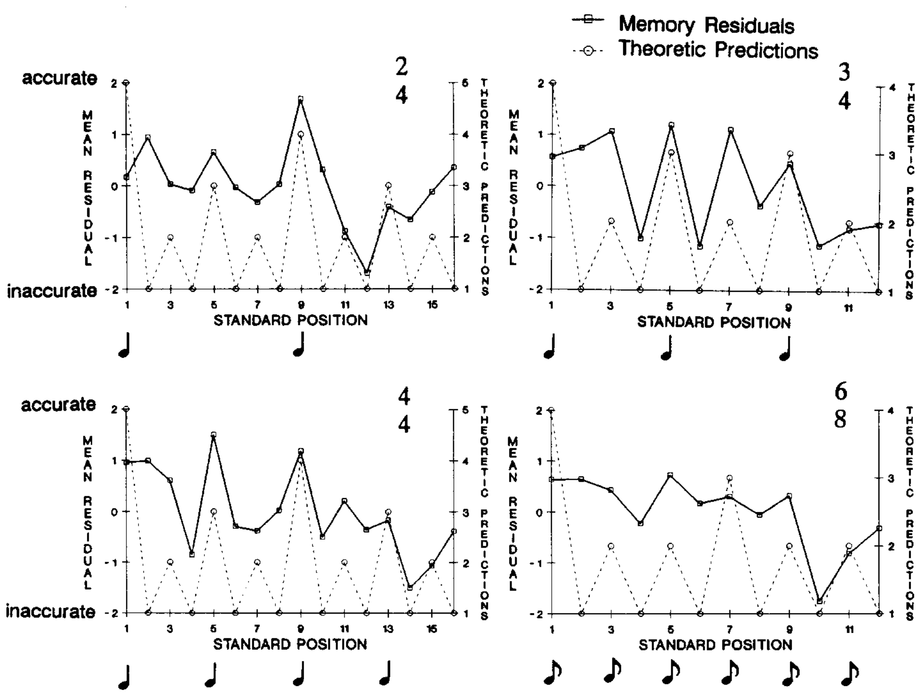

Figure 5. Mean residuals from discrimination ratings with serial distance effects removed (solid line) and theoretic predictions (dashed line) by metrical context.

General Discussion

We have described initial attempts to specify how temporal relationships are perceived and remembered when a specific meter is suggested by a temporal context. These studies show that the perceived relatedness between individual temporal events is significantly altered by the suggested metrical context. The alterations reflect a mental hierarchy of periodic accent placement or stability, which is central to the definition of metrical structure. In a metrical system, musical events vary in their stability within a metrical hierarchy, with some events highly accented, some events less accented, and accents at each level equally spaced apart.

In previous sections we introduced several sources of evidence for a multileveled hierarchical representation of meter, including music-theoretic predictions (Lerdahl & Jackendoff, 1983), frequency distributions in musical compositions, goodness-of-fit judgments for temporal sequences, and memory confusions from discrimination judgments. The compatibility among the sources of evidence indicates that frequencies of events placed in different temporal locations in musical compositions correspond to perceived accent strength and serve to reinforce an inferred meter. Likewise, memory associations reflect relative metrical strength of temporal locations. The music-theoretic accounts of hierarchical accent structure correlate well with each of the three variables, providing experimental support for a theory of metrical structure in Western tonal music (Lerdahl & Jackendoff, 1983). It is unlikely that mental representations for meter are learned through formal training; very few of the listeners in these experiments had had exposure to music theory. Rather, the rhythmic organization of temporal patterns appears to be instantiated in the frequency with which events occur in various metrical positions in Western tonal music and affects perceived relatedness and memory strength.

This article has addressed how metrical contexts influence perception, memory, and musical composition of temporal sequences. Thus, features that specifically reflect temporal structure were emphasized rather than tonal, harmonic, and intensity structures that function in music as well. Abstract knowledge frameworks for these musical dimensions may play similar roles in perception and composition. For instance, abstract knowledge of tonal organization influences perception of single events in a tonal context (Krumhansl, 1983; Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979). In this work, evidence was found for three levels of organization in an internalized tonal structure: musical tones, chords, and keys. Each level describes associations between elements, and perceived stability of events is predicted from a hierarchy of relatedness among elements at each level. This knowledge system influences encoding, interpretation, and memory in musical tasks. In a similar manner, complex knowledge of meter appears to influence perceiving, remembering, and composing music through interconnections at each level in a metrical hierarchy.

A related question concerns the issue of how these complex knowledge structures for different musical dimensions combine. Although little direct evidence is available, a suggestion comes from the high correspondence in metrical frameworks seen here across different compositional styles. The high degree of complexity among multiple musical dimensions may promote composers to make a metrical framework apparent to guide the listener toward anticipation of events in other musical dimensions. Ample evidence exists to support the role of rhythmic and harmonic regularities in music creating anticipations or musical expectations (Carlsen, 1981; Meyer, 1956). For instance, listeners' ratings of continuations for incomplete musical passages indicate that expectations are well predicted by reference to harmonic regularities in Western tonal music (Schmuckler, 1989). In addition, temporal regularity, as supplied by a rhythmic context, affects listeners' abilities to gauge temporal order of tones embedded in musical sequences (Jones, Kidd, & Wetzel, 1981). These findings suggest that metrical regularities can aid listeners in developing expectations on temporal as well as other musical dimensions.

Perceptual cues to meter other than event locations have been suggested; the most common of these is duration (Fraisse, 1982; Longuet-Higgins & Lee, 1982). How can the multileveled metrical representation suggested here fit with earlier findings (Fraisse, 1982) that 80% of events in musical excerpts were accounted for by only two durations (usually the briefest durations in the piece)? To define the lowest levels of a metrical hierarchy (those corresponding to the shortest periodicities or time spans), events must be sounded at adjacent temporal locations within a level. Thus, there must be many events of short durations to establish the lowest level. Higher levels can be instantiated by events of short or long durations. Therefore, if meter is instantiated primarily by the frequency of events in different temporal locations (rather than their durations), then there is no need for many different durations. The only requirement is that the durations be sounded in many different temporal locations (to establish each metrical level). Thus, these results are not contradictory with earlier findings (Fraisse, 1982) if event locations rather than durations signal meter.

The notion of a hierarchy of metric organizational levels is common in music-theoretic approaches (Cooper & Meyer, 1960; Lerdahl & Jackendoff, 1983) as well as psychological conceptualizations of rhythmic structure (Jones, 1976; Martin, 1972; Povel, 1981). The advantages of hierarchical models include musical insights concerning meter formation and psychological insights concerning perceptual expectancies (Handel, 1984). The hierarchical nature of meter emphasizes the separation of tempo, or absolute rate, from the relative timing among events (Handel, 1984). The tempo can be specified at the lowest level (smallest time units), and the relative timings among events at each level will remain invariant across tempos. Therefore, the same abstract knowledge of meter can accommodate a musical composition performed at different rates. The prediction and anticipation of future events is also facilitated by the separation of tempo and relative timing, allowing efficient attentional strategies to be used by a listener.

There are many parallels between the hierarchical organization of metrical structure in music and in other cognitive domains. In speech, tapping, and other serial behaviors, certain events serve as accents or points of relative importance. Models developed for tapping behavior, for instance, indicate the existence of higher order rhythmic units that are taken as evidence for hierarchical organization in the control of timing (Vorberg & Hambuch, 1978). The rhythm of spoken language contains multileveled accent patterns as well (Martin, 1972; Selkirk, 1984). In the majority of spoken languages, accented syllables tend to occur at equal intervals; these are called stress-timed languages. Stress is marked in speech with acoustic intensity, frequency, or duration. The stress pattern of a language can be analyzed at many levels: at the segmental level, the syllable level, the word level, and the sentence level. As in traditional Western music, events in stress-timed languages tend to occur at equal temporal intervals within each level of stress (Selkirk, 1984); the metrical stress of event locations contributes to their perceived relative importance (Fowler & Housum, 1987; Martin, 1972).

In summary, the present findings indicate that listeners have acquired underlying principles of the hierarchical functioning of temporal events within metrical frameworks. Listeners make reference to this knowledge of the temporal regularities underlying music to encode and remember musical events, affecting the perceived association among events and producing a mental representation of coherence among multiple metrical levels. The perceived associations depend on the particular metrical context inferred by the listener, and explanations of metrical structure based solely on sensory cues must be incomplete. The present findings extend music-theoretic and psychological accounts of hierarchical processes presumed to be operating during listening by characterizing relations among the compositional, perceptual, and memory organization of musical meter.

References

Apel, W. (1972). *Harvard dictionary of music* (2nd ed.). Cambridge, MA: Harvard University Press.

Benjamin, W. (1984). A theory of musical meter. *Music Perception, 1*, 355–413.

Berry, W. (1976). *Structural functions in music.* Englewood Cliffs, NJ: Prentice-Hall.

Bharucha, J. J., & Krumhansl, C. L. (1983). The representation of harmonic structure in music: Hierarchies of stability as a function of context. *Cognition, 113*, 63–102.

Bharucha, J. J., & Pryor, J. H. (1986). Disrupting the isochrony underlying rhythm: An asymmetry in discrimination. *Perception & Psychophysics, 40*, 137–141.

Carlsen, J. C. (1981). Some factors which influence melodic expectancy. *Psychomusicology, 1*, 12–29.

Cohen, A. J., Trehub, S. E., & Thorpe, L. A. (1989). Effects of uncertainty on melodic information processing. *Perception & Psychophysics, 46*, 18–28.

Cohen, J. E. (1962). Information theory and music. *Behavioral Science, 7*, 137–163.

Cooper, G. W., & Meyer, L. B. (1960). *The rhythmic structure of music.* Chicago: Chicago University Press.

Deutsch, D. (1980). The processing of structured and unstructured tonal sequences. *Perception & Psychophysics, 28*, 381–389.

Fowler, C. A., & Housum, J. (1987). Talkers signalling of "new" and "old" words in speech and listeners' perception and use of the distinction. *Journal of Memory and Language, 26*, 489–504.

Fraisse, P. (1956). *Les structures rhythmiques* [Rhythmical Structures]. Louvain, France: Editions Universitaires.

Fraisse, P. (1982). Rhythm and tempo. In D. Deutsch (Ed.), *The psychology of music* (pp. 149–181). New York: Academic Press.

Gabrielsson, A. (1974). Similarity ratings and dimension analyses of auditory rhythm patterns. II. *Scandinavian Journal of Psychology, 14*, 161–176.

Garner, W. R. (1974). *The processing of information and structure.* Potomac, MD: Erlbaum.

Handel, S. (1984). Using polyrhythms to study rhythm. *Music Perception, 1*, 465–484.

Handel, S., & Lawson, G. R. (1983). The contextual nature of rhythmic interpretation. *Perception & Psychophysics, 34*, 103–120.

Hutchinson, W., & Knopoff, L. (1987). The clustering of temporal elements in melody. *Music Perception, 4*, 281–303.

Jenkins, G. M., & Watts, D. G. (1968). *Spectral analysis and its applications.* San Francisco: Holden-Day.

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review, 83*, 323–335.

Jones, M. R., Boltz, M., & Kidd, G. (1982). Controlled attending as a function of melodic and temporal context. *Perception & Psychophysics, 32*, 211–218.

Jones, M. R., Kidd, G., & Wetzel, R. (1981). Evidence for rhythmic attention. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 1059–1073.

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

Krumhansl, C. L. (1983). Perceptual structures for tonal music. *Music Perception, 1*, 28–62.

Krumhansl, C. L., & Kessler, E. J. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Psychological Review, 89*, 334–368.

Krumhansl, C. L., & Shepard, R. N. (1979). Quantification of the hierarchy of tonal functions within a diatonic context. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 579–594.

Lerdahl, F., & Jackendoff, R. (1983). *A generative theory of tonal music.* Cambridge, MA: MIT Press.

Lewin, D. (1984). On formal intervals between time-spans. *Music Perception, 1*, 414–423.

Longuet-Higgins, H. C. (1979). The perception of music. *Proceedings of the Royal Society of London, 205*, 307–322.

Longuet-Higgins, H. C., & Lee, C. S. (1982). The perception of musical rhythms. *Perception, 11*, 115–128.

Martin, J. G. (1972). Rhythmic (hierarchical) versus serial structure in speech and other behavior. *Psychological Review, 79*, 487–509.

Meyer, L. (1956). *Emotion and meaning in music.* Chicago: University of Chicago Press.

Monahan, C. B., & Carterette, E. C. (1985). Pitch and duration as determinants of musical space. *Music Perception, 3*, 1–32.

Nakamura, T. (1987). The communication of dynamics between musicians and listeners through musical performance. *Perception & Psychophysics, 41*, 525–533.

Palmer, C. (1988). *Timing in skilled music performance.* Unpublished doctoral dissertation, Cornell University, Ithaca, NY.

Palmer, C. (1989). Mapping musical thought to musical performance. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 331–346.

Pinkerton, R. C. (1956). Information theory and melody. *Scientific American, 194*, 77–82.

Povel, D. J. (1981). The internal representation of simple temporal patterns. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 3–18.

Povel, D. J., & Essens, P. (1985). Perception of temporal patterns. *Music Perception, 2*, 411–440.

Royer, F. L., & Garner, W. R. (1966). Response uncertainty and

perceptual difficulty of auditory temporal patterns. *Perception & Psychophysics, 1,* 41–47.
Schmuckler, M. S. (1989). Expectation in music: Investigation of melodic and harmonic processes. *Music Perception, 7,* 109–150.
Selkirk, E. O. (1984). *Phonology and syntax: The relation between sound and structure.* Cambridge, MA: MIT Press.
Shaffer, L. H., Clarke, E. F., & Todd, N. P. (1985). Metre and rhythm in piano playing. *Cognition, 20,* 61–77.
Shaffer, L. H., & Todd, N. P. (1987). The interpretive component in musical performance. In A. Gabrielsson (Ed.), *Action and perception in rhythm and music* (pp. 139–152). Stockholm, Sweden: Royal Swedish Academy of Music.
Sloboda, J. A. (1983). The communication of musical metre in piano performance. *Quarterly Journal of Experimental Psychology, 35,* 377–396.
Sloboda, J. A. (1985). *The musical mind.* Oxford, England: Oxford University Press.
Steedman, M. (1977). The perception of musical rhythm and meter. *Perception, 6,* 555–570.
Vorberg, D., & Hambuch, R. (1978). On the temporal control of rhythmic performance. In J. Requin (Ed.), *Attention and performance VII* (pp. 535–555). Hillsdale, NJ: Erlbaum.
Vos, P. (1976). *Identification of metre in music.* (Report No. 76 ON 06). University of Nijmegen, Nijmegen, The Netherlands.
Vos, P. (1977). Temporal duration factors in the perception of auditory rhythmic patterns. *Scientific Aesthetics, 1,* 183–199.
Woodrow, H. (1951). Time perception. In S. S. Stevens (Ed.), *Handbook of experimental psychology* (pp. 1224–1236). New York: Wiley.
Youngblood, J. E. (1958). Style as information. *Journal of Music Theory, 2,* 24–35.

Received October 23, 1989
Revision received February 8, 1990
Accepted February 9, 1990 ■