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Infants use meter to categorize rhythms and melodies: Implications for musical structure learning☆

Erin E. Hannon[a,*], Scott P. Johnson[b]

[a] *Department of Psychology, Cornell University, Ithaca, NY, USA*
[b] *New York University, USA*

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Abstract

Little is known about whether infants perceive meter, the underlying temporal structure of music. We employed a habituation paradigm to examine whether 7-month-old infants could categorize rhythmic and melodic patterns on the basis of the underlying meter, which was implied from event and accent frequency of occurrence. In Experiment 1, infants discriminated duple and triple classes of rhythm on the basis of implied meter. Experiment 2 replicated this result while controlling for rhythmic grouping structure, confirming that infants perceived metrical structure despite occasional ambiguities and conflicting group structure. In Experiment 3, infants categorized melodies on the basis of contingencies between metrical position and pitch. Infants presented with metrical melodies detected reversals of pitch/meter contingencies, while infants presented with non-metrical melodies showed no preference. Results indicate that infants can infer meter from rhythmic patterns, and that they may use this metrical structure to bootstrap their knowledge acquisition in music learning.

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* Corresponding author. Fax: +1 905 569 4326.
E-mail address: eeh5@cornell.edu (E.E. Hannon).

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1. Introduction

Infants are confronted with rapidly changing, complex auditory patterns such as music and speech from before the time they are born. A question of great interest is how infants learn to organize, parse, and interpret these patterns. Increasing behavioral and computational evidence suggests that infants can use distributional properties of input, such as frequency of occurrence, co-occurrence of syllables or units, and the alternation of strong and weak units, to learn about structure in language and music (Christiansen, Allen, & Seidenberg, 1998; Mattys & Jusczyk, 2001; Maye, Werker, & Gerken, 2002; Saffran, Aslin, & Newport, 1996; Thiessen & Saffran, 2003). The term "distributional" refers to the frequency with which elements or combinations of elements occur in any type of input. Rhythmic information might be particularly important in guiding how infants perceive distributional information in auditory patterns. For example, newborn infants appear to discriminate native from non-native languages on the basis of rhythmic structure (Nazzi, Bertoncini, & Mehler, 1998; Nazzi, Jusczyk, & Johnson, 2000), an ability that may facilitate subsequent language learning (Curtin, Mintz, & Christiansen, in press; Cutler, 1994). Rhythmic structure might also play a fundamental role in infants' early musical experiences and music learning. The present work asks whether infants can use the distributional information in music to infer its underlying temporal organization, and whether this temporal organization might function as a framework for learning other complex structures in music.

Two interacting aspects of temporal structure characterize musical rhythm: *rhythmic pattern* and *meter*. A rhythmic pattern can be most simply defined as a series of temporal intervals. Fig. 1 (top) depicts a rhythmic pattern in musical notation and in graphical form, made up of a distinctive series of short and long temporal intervals having 250 and 500 ms durations. Meter, in contrast, is the abstract temporal structure of music, composed of multiple nested periodic structures, the most salient of which is experienced as the "beat," the point in time where most people tap their fingers or feet to the music. Unlike rhythmic pattern structure, which corresponds to the specific pattern of temporal intervals in a sequence, metrical structure must be inferred from periodic regularities in the musical surface (Clarke, 1999; Palmer & Krumhansl, 1990). Listeners tend to infer from music a primary, periodic cycle marked by equally spaced (i.e., "isochronous") beats, plus one or two faster or slower isochronous levels that subdivide or multiply the primary cycle. Two common types of metrical subdivisions are *duple*, in which the primary cycle is subdivided into four or two beats, and *triple*, in which it is subdivided into three beats. This hierarchical structure creates alternating patterns of perceived strong and weak beats in music, as in the triple meter waltz pattern of "*one* two three, *one* two three …" illustrated in Fig. 1. Note that during first cycle of the meter the rhyth-

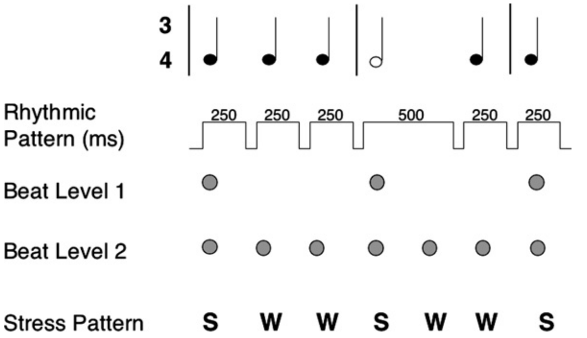

Fig. 1. A metrical hierarchy typical of a waltz is depicted in musical notation and graphical form. For the triple meter time signature 3/4, the denominator specifies the base unit (a quarter-note) and the numerator specifies the number of units per cycle. Alternating strong (S) and weak (W) beats arise from the metrical hierarchy, which consists of two isochronous beat levels.

mic pattern is composed of three short intervals, while during the second cycle it is composed of a long interval followed by a short interval; this illustrates that the rhythmic pattern can and often does vary independent of the meter. Metrical structure enables individuals in a group to synchronize their movements in dancing, marching, tapping, clapping, and singing, allowing for precise anticipation of when movements should occur. Metrical structure is also thought to guide attention, enhancing anticipation for what is likely to occur and when it will occur, and aiding in segmentation of musical sequences into melodic and rhythmic groups (Jones & Boltz, 1989; Large & Jones, 1999; Palmer & Pfordresher, 2003). Because synchronized coordination of movement to music has been observed in all known cultures, meter is thought to constitute a fundamental and universal aspect of musical perception and behavior (Brown, 2003).

It is difficult to predict exactly how a musical sequence will give rise to a subjective pattern of periodic strong and weak beats, but distributional regularities are likely to serve as essential cues. In Western music, composers use time signature notation to specify the intended meter. For example, the time signature 3/4, which corresponds to the meter depicted in Fig. 1, signifies that the primary metrical cycle is subdivided into three beats, the first of which has the greatest metrical strength. For a given meter, note onsets, or events, tend to occur more frequently at strong (downbeat) rather than weak (upbeat) positions in the primary metrical cycle. The frequency of event occurrence has been shown to predict the meter of musical excerpts from four styles of Western classical music (Palmer & Krumhansl, 1990) and children's nursery tunes (Palmer & Pfordresher, 2003). Thus, musical events, such as the sounding of a piano or the beating of a drum, are much more likely to occur every second or fourth beat in duple meters and every third beat in triple meters. A second type of distributional cue to meter is *accent*. Accents arise when events are relatively salient, due to being longer, louder, higher in pitch, positioned at points of change in a melody, or at melodic and/or rhythmic group boundaries. For the remainder of the paper, our use of the term *accent* will denote such *phenomenal* accents, to be distinguished from *metrical* accents, which arise from the pattern of strong and weak beats that are perceived after a metrical representation has been activated (Lerdahl & Jackendoff, 1983). Analyses of various styles of western music revealed that accents tend to occur frequently at metrically strong positions in a given time signature (Huron & Royal, 1996; Longuet-Higgins & Lee, 1982). Frequency of events and accents are thus reliable distributional cues to meter.

The widespread occurrence of synchronized dancing, tapping, and other types of rhythmic behavior attests to the relative ease with which adults can grasp the intended metrical structure of most music. Several studies have shown that adults accurately synchronize their tapping with strong metrical positions in music, exhibiting a high level of inter-subject agreement (Drake, Penel, & Bigand, 2000; Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003). Frequency of accents at potential downbeat positions reliably predicts tapping position (Snyder & Krumhansl, 2001) and the perceived meter (Hannon, Snyder, Eerola, & Krumhansl, 2004). Adults thus appear to use the distribution of accents and events over time to infer metrical structure.

Unlike adults, infants are not capable of producing precisely timed rhythmic behaviors such as synchronized tapping. However, their rhythmic pattern perception parallels that of adults in important respects. Like adults, 2- and 5-month-old infants can use the relative size and order of intervals to discriminate rhythmic patterns, such as 600–200–400 vs. 200–600–400 ms (Chang & Trehub, 1977; Demany, McKenzie, & Vurpillot, 1977). Seven- and 9-month-old infants can categorize stimuli on the basis of identical rhythmic pattern structure, despite concurrent transformations of frequency and tempo (Trehub & Thorpe, 1989; but see Pickens & Bahrick, 1997). Thus adults and infants both tend to perceive rhythmic patterns in terms of global and relational information and not in terms of the component temporal intervals that compose a pattern (Trehub, Trainor, & Unyk, 1993).

Infants' abilities for discriminating and categorizing stimuli on the basis of rhythmic pattern structure can be considered a prerequisite for perceiving meter, because rhythmic patterns are thought to guide meter induction in important ways. For example, temporal accents can arise from the position of an event in relation to the rhythmic grouping of a pattern, or the way in which events are clustered in time (Lerdahl & Jackendoff, 1983). An event tends to sound accented if it is surrounded by silence (isolated), or if it falls at a boundary of a group of events surrounded by silence (Povel & Essens, 1985). Thus, if infants are sensitive to the rhythmic grouping of events, they may also hear subjective temporal accents that might enable them to infer meter. Nevertheless, only indirect evidence suggests that infants perceive meter.

Metrical information is salient in the environment of young infants, who are frequently rocked and bounced to music (Papousek, 1996). When mothers sing to their infants, they tend to emphasize metrically stressed syllables through small increases in duration and loudness (Trainor, Clark, Huntley, & Adams, 1997). Such changes are noticed by 10-month-old infants, who distinguished otherwise identical musical segments performed in different metrical contexts (Palmer, Jungers, & Jusczyk, 2001). As early as 2 months, infants can detect changes to the speed of an isochronous pattern, which might reflect a rudimentary form of meter perception (Baruch & Drake, 1997). Nine-month-old infants detect temporal deviations to rhythmic patterns better when those patterns induce a strong metrical framework (Bergeson, 2002). These findings indirectly suggest that infants perceive meter. A primary goal of the present work was to directly tackle this question by measuring whether infants could categorize unique rhythms on the basis of a common underlying meter. Such a result would provide the strongest evidence to date that infants perceive metrical structure in musical patterns.

A secondary goal was to investigate whether meter, if perceived by infants, might serve to facilitate other aspects of music learning. Studies of speech perception have shown that distributional cues can interact in important ways, with certain types of cues providing a foundation for learning other types of information. For example, stress is a reliable distributional cue to word boundaries in English because most words begin with stressed syllables. At 7–9 months of age, infants exploit this regularity to segment words with initial stress from fluent speech (Curtin et al., in press; Jusczyk, Houston, & Newsome, 1999). Unlike 7-month-olds, 9- to 11-month-old infants can correctly segment words having the atypical weak–strong pattern (Jusczyk et al., 1999; cf. Thiessen & Saffran, 2003). The superior performance of older infants presumably results from the acquisition of additional knowledge about word boundaries that overrides stress, such as *phonotactic* regularities, which are the sequences of speech sounds that are typical within vs. between words (Jusczyk et al., 1999; Myers et al., 1996). Although various cues to word boundaries are probably learned simultaneously, an initial tendency to associate stressed vs. unstressed syllables with different speech sounds may highlight word boundaries, facilitating acquisition of knowledge about other segmentation cues in language (Christiansen et al., 1998; Curtin et al., in press; Jusczyk, 1999). A similar type of bootstrapping process may exist in musical structure learning (Jones, 1990). If infants can use the distribution of event and accent occurrence to infer the meter, the meter may in turn serve as a framework for learning about other aspects of pitch structure in music by highlighting particular events in a sequence.

To summarize, little is known about whether infants perceive the underlying temporal structure of music, the meter. Distributional information, such as frequency of event and accent occurrence, reliably predicts the meter perceived by adults. Infants' general sensitivity to distributional cues in auditory patterns, as well as their adult-like perception of rhythmic patterns, suggests that they might be able to use event and accent occurrence to infer meter. In the first two experiments, we examine whether infants can infer meter from simple rhythmic patterns. If they can, they should be able to differentiate new rhythmic patterns that conform to the inferred meter from those that do not. In the third experiment, we examine whether infants can learn to associate musical pitches with strong or weak positions in the meter.

2. Experiment 1

The first experiment assessed whether infants could use distributional cues to infer the underlying meter of simple rhythmic patterns. Previous studies have shown that infants respond similarly to unique instances of a stimulus if those instances have the same structure or fall into the same category (Trehub & Thorpe, 1989). If infants perceive metrical structure, they should respond similarly to a set of unique rhythmic patterns that induce the same meter. In Experiment 1, 7-month-old infants were habituated to an audio–visual display that presented three different rhythms having the same underlying meter. Following habituation, infants were presented with two novel rhythms that implied a novel or a familiar meter. If infants perceive meter, they should exhibit differential looking for rhythmic patterns that imply a novel vs. familiar meter.

2.1. Method

2.1.1. Participants

Twenty-four 7-month-old infants (*M* age = 217.7 days, *SD* = 4.4) participated, 11 girls and 13 boys. Three additional infants were tested but not included in the sample due to fussing (*N* = 3), or experimenter error (*N* = 1). All participants were healthy, full-term infants with no complications during delivery and no reported health or hearing problems.

2.1.2. Stimuli

Eight rhythms were composed of 24 temporal units that were 250 ms in duration, nine of which were *silent* units and 15 of which were *event* units. Event units consisted of a 100 ms tone at the pitch level of C5 (523 Hz), followed by 150 ms of silence. The brief duration of tones gave them a staccato quality. Tones were generated using Quicktime's *Ocarina* timbre, which approximates a sine tone. Silent units were 250 ms in duration. Two consecutive event units resulted in a 250 ms inter-onset interval, while two consecutive silent units resulted in a cumulative silence of 500 ms. The longest possible silent duration was 500 ms, and this occurred at least once in each rhythm. Fig. 2 depicts the temporal properties of a brief segment of one rhythm in iconic form, with event units designated by "×" and silent units designated by "o".

Rhythms were created to imply either a duple meter or a triple meter. In triple meter, events and accents occurred more frequently on the first of every three units (and less frequently at all other positions), and in duple meter they occurred more

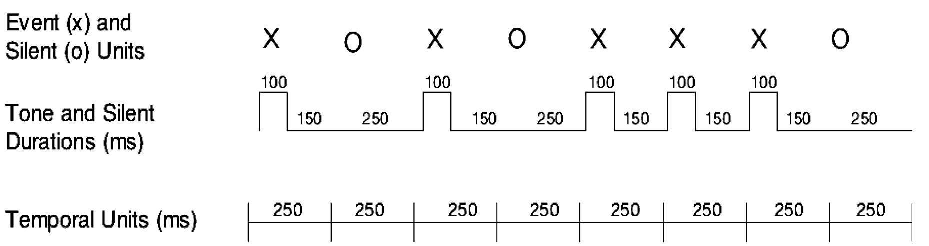

Fig. 2. An iconic depiction of a rhythm segment. Temporal units of 250 ms were either silent units (250 ms, depicted as "o"), or event units (100 ms tone followed by 150 ms silence, depicted as "×").

frequently on the first of every four or two units. To minimize differences between rhythms, we avoided physically altering the amplitude or pitch level of accented vs. unaccented events, instead focusing on the subjective accents that arise from the positioning of events relative to rhythmic groups. We hypothesized, based on previous adult research, that events would sound accented if they were relatively isolated, the second of a two-event group, or the first or last event in a group larger than three (Povel & Essens, 1985). We thus manipulated the frequency distribution of accents and events by assigning an event or silence to each temporal unit quasi-randomly, with the following constraints adapted from Povel and Essens (1985): (a) no silences occurred at strong metrical positions, (b) events in strong positions could not be both preceded and followed by other events, (c) events in weak positions could not be followed by silence. The first constraint ensured that events occurred more frequently at strong metrical positions, while the other constraints ensured that accents occurred more frequently at strong than at weak metrical positions by keeping strong events isolated or at group boundaries (b) and preventing weak events from being relatively isolated or occurring at the end of a group boundary (c). For triple meter rhythms, every third unit was designated as metrically strong. Because theoretical descriptions of duple meter distinguish between the primary downbeat, which would occur every four units, and the secondary downbeat, which would occur every two units, we used all four constraints for primary downbeat units (every four), and constraint (c) for secondary downbeat units (every two). This resulted in a slightly lower frequency of accents and events at secondary vs. primary metrical positions.

Using these constraints, we generated four unique rhythms in each meter (Fig. 3). Rhythms were differentiated by the distribution of events and accents (in bold) at strong vs. weak positions in triple or duple meter. Fig. 4 displays the average proportion of events and accents that occurred for every two, three, or four units of the duple and triple meter stimuli. As intended, duple meter stimuli had a higher

Duple Rhythms

D1: |**x** o **x** o|**x** x **x** o|**x** o o x|**x** o **x** o|**x** x x x|**x** o o x|

D2: |**x** o o x|**x** o o x|**x** o **x** x|**x** o **x** o|**x** x x x|**x** o **x** o|

D3: |**x** x **x** o|**x** x x x|**x** o o x|**x** o **x** o|**x** o o x|**x** o **x** o|

D4: |**x** o o x|**x** o **x** o|**x** x x x|**x** o **x** x|**x** o o x|**x** o **x** o|

Triple Rhythms

T1: |**x** x x|**x** o x|**x** o x|**x** o o|**x** o x|**x** o o|**x** x x|**x** o o|

T2: |**x** o o|**x** x x|**x** o x|**x** o o|**x** o o|**x** x x|**x** o x|**x** o x|

T3: |**x** o x|**x** o x|**x** o o|**x** x x|**x** o o|**x** o x|**x** o o|**x** x x|

T4: |**x** x x|**x** o x|**x** o o|**x** x x|**x** o x|**x** o o|**x** o x|**x** o o|

Fig. 3. Rhythmic patterns used in Experiment 1. ×, event unit; o, silent unit. Accents are indicated in bold.

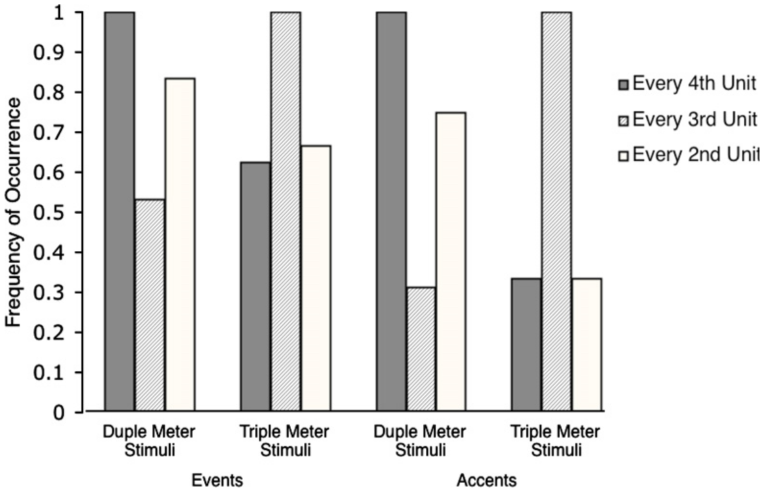

Fig. 4. The average proportion of event and accent occurrence is shown for downbeats in duple meter (every fourth unit), downbeats in triple meter (every third unit), and secondary downbeats in duple meter (every second event). The proportion was calculated by dividing the number of times an accent or event occurred by the total number of potential downbeat units in each rhythm.

proportion of events and accents occurring every two or four units, while triple meter stimuli had the highest proportion of events and accents occurring every three units.

Even though previous findings suggested that adults use frequency of event and accent occurrence to infer the metrical structure (Hannon et al., 2004; Povel & Essens, 1985; Snyder & Krumhansl, 2001), we collected pilot data to ensure that our stimuli sounded metrical to adults. Three expert musicians[1] rated each rhythm's degree of fit to both triple and duple meter. We subtracted the average ratings for triple fit from those for duple fit to obtain a judgment scale ranging from strong duple fit (positive) to strong triple fit (negative). As predicted, ratings were significantly higher for the four rhythms we had designated duple than for the four rhythms we had designated triple, $p < .01$. In other words, duple rhythms sounded much more "duple" than triple rhythms and vice versa. Because accented events were physically indistinguishable from non-accented events, we also wanted to verify that intended accents were perceived as such by asking musicians to mark which events sounded accented. The average match between perceived and intended accents was 90%, indicating that most accents were reliably perceived. We also assessed whether non-musically trained adults could differentiate the stimuli on the basis of implied meter. In a paired comparison task, adults indicated which of two novel comparison rhythms had the same underlying beat as two standard rhythms with 75% accuracy, which was significantly above chance, $p < .001$.

[1] Three musicians had an average of 25 years music lessons and advanced music degree certification and/or training from Moscow State Conservatory College of Music, Royal Conservatory of Toronto, and Eastman School of Music.

Although performance was only moderately accurate, we suspect the task was somewhat difficult because of adults' known tendency to interpret rhythms in duple meter, perhaps due to the greater prevalence of duple meters in Western music (Hannon et al., 2004).

Each 6 s rhythmic pattern was cycled 10 times to create a maximum trial duration of 60 s. All rhythms were combined with a video display and converted into QuickTime movies. The video display consisted of an unmoving black and white checkerboard that filled the screen and remained present throughout the duration of each trial.

2.1.3. Apparatus

A Macintosh G4 computer and a 76 cm monitor equipped with a speaker were used to present audio–visual stimuli and collect looking time data. A camera placed on top of the monitor recorded the infant and transmitted the image to a second monitor behind a large barrier. The experimenter viewed the infant on the second monitor and entered judgments of infant gaze with a key press on a computer keyboard. Because the monitor speakers presented the rhythms, infant head turns towards the monitor also reflected turns toward the sound source. The computer presented the audio–visual stimuli (i.e., the checkerboard and rhythmic patterns), recorded looking time judgments, and calculated habituation criteria for each infant. The experimenter and parent wore headsets playing music to mask the stimulus sounds.

2.1.4. Procedure

Infants were tested individually and sat on their parents' laps in a darkened room, at a distance of 90 cm and turned at a 45° angle to the left of the monitor. This angle required a slight head turn towards the monitor. All trials were initiated as soon as the infant fixated on the monitor, and terminated when the infant looked away for more than 2 s. Between trials, the computer presented a looming target accompanied by a rapidly pulsed siren to orient the infants' attention towards the monitor.

During the habituation phase, each infant was presented with a series of three rhythms all in the same meter. The order of rhythm presentation on habituation trials was quasi-random, with the restriction that all three rhythms had to be presented before a given rhythm could be repeated. Each infant was assigned to one of two habituation conditions, in which the meter of the habituation rhythms was duple or triple. Infants were habituated to the sequence of three rhythms until habituation of looking occurred or 12 trials had elapsed. The habituation criterion was defined as an average fixation decrement of 50% over four trials relative to the average fixation of the previous four trials.

Immediately following habituation trials, infants were presented with six test trials, consisting of three alternating presentations of two novel rhythms, one from a novel meter and one from a familiar meter. Order of post-habituation test trials was counter-balanced in each condition, so that half of the infants were presented with a novel meter rhythm first, and half were presented with a familiar meter rhythm first.

The rhythms used during habituation vs. test phase were alternated throughout the experiment, so that all rhythms occurred during both the habituation and test phases of the experiment.

2.2. Results and discussion

Infants oriented longer towards the post-habituation test rhythm that implied a novel meter than towards the test rhythm that implied a familiar meter (see Fig. 5). Looking time data were positively skewed in some cells, so all data were log-transformed prior to analyses (data shown in Fig. 5 are raw scores). A three-way, mixed design ANOVA, with test condition (novel vs. familiar meter, within subjects), habituation condition (triple vs. duple meter, between subjects), and test order (novel meter first vs. familiar meter first, between subjects), revealed a significant main effect of test condition, $F(1, 20) = 7.05$, $p < .05$. There were no other significant main effects or interactions with habituation condition or test order.

This result suggests that infants inferred the underlying meter from the three rhythms presented in the habituation phase, which resulted in a novelty preference for the test rhythm that induced a novel meter. Because all rhythms were identical in length and in the number of events and silences, it is likely that the distribution of event and accent occurrence was the primary differentiating feature of triple vs. duple meter rhythms. We assume that infants inferred periodic accents from the positioning of events relative to rhythmic groups, but it is possible that infants simply noticed and remembered the grouping structure (the number and size of groups). Because group size was also a differentiating feature of these rhythms, we conducted a second experiment to separately assess the effects of grouping structure vs. implied meter on infant behavior.

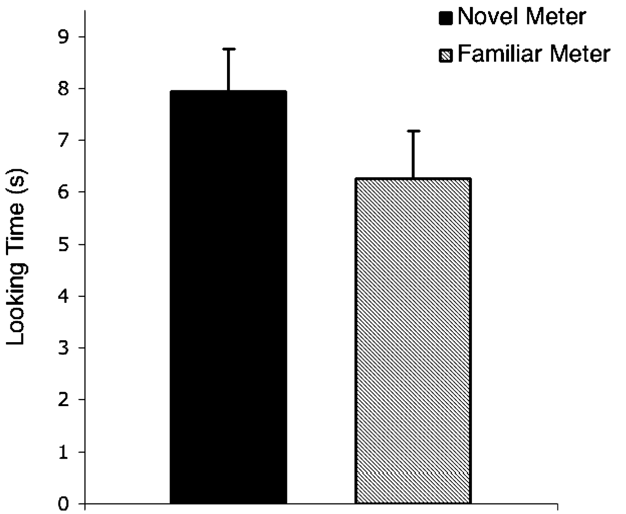

Fig. 5. Mean looking times after habituation (in seconds). Error bars indicate standard errors. Infants looked longer during presentation of a novel meter rhythm.

3. Experiment 2

The triple and duple meter stimuli used in Experiment 1 were differentiated by the distribution of events and accents as well as by the number of events per group. We define a group as any series of events bordered on both sides by silence. An unintended outcome of the constraints used to generate stimuli in Experiment 1 was that some group sizes occurred exclusively in one meter and not in the other. In Fig. 6, all groups in four rhythms have been circled and labeled according to size, i.e., the number of events within each group. Notice that for Experiment 1 (Figs. 6 top and 3), duple rhythms contained groups of 1, 2, 3, and 5, while triple rhythms contained groups of 1, 2, and 4. Groups of three events, for example, occurred in duple but not triple meter rhythms. This is because groups of three events were inherently problematic for generating a metrically appropriate distribution of events and accents. To illustrate, a group of three events starting at a downbeat position in triple meter would leave the subsequent downbeat silent, which violates the constraint that events should always occur at strong metrical positions.

Previous studies have shown that 12-month-old infants can discriminate rhythmic patterns on the basis of group size differences (Morrongiello, 1984), so it is possible that infants categorized rhythms in Experiment 1 on the basis of group size. This possibility would be consistent with the hypothesis that infants process rhythmic patterns according to serial structure, and that they have not yet developed the ability to infer the complex hierarchical aspects of metrical structure (Drake, 1998). To disentangle the effects of grouping structure and meter, we replicated Experiment 1 using test rhythms that pitted grouping structure against implied meter.

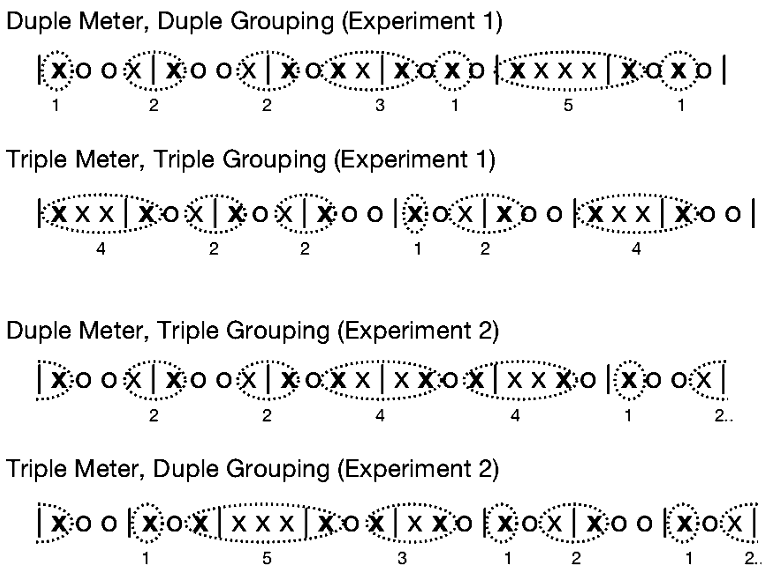

Fig. 6. Rhythmic patterns used in Experiment 2. ×, tone; o, silence. Each group is circled with a dashed line, and group sizes are labeled beneath. Accents are indicated in bold.

3.1. Method

3.1.1. Participants

Twenty-four 7-month-old infants (*M* age = 220.4 days, *SD* = 15.9) participated, 14 girls and 10 boys. Two additional infants were observed but not included in the sample due to fussing. All participants were healthy, full-term infants with no complications during delivery and no reported health or hearing problems.

3.1.2. Stimuli

The same rhythms from Experiment 1 were used during the habituation phase. Two additional rhythms were created for use during the test phase. As in Experiment 1, test rhythms were composed of 24 temporal units, made up of nine silences and 15 tones. The pitch, timbre, durations, and inter-onset intervals of the rhythms were identical to those used in Experiment 1.

In Experiment 1, all rhythms in a given meter were identical in grouping structure. As shown in Figs. 6 and 3, duple meter rhythms always contained three groups of one, two groups of two, one group of three, and one group of five, while triple meter rhythms contained one group of one, three groups of two, and two groups of four. To create test rhythms for Experiment 2, the grouping structure of each meter was rearranged according to the metrical constraints of the contrasting meter, to the maximum extent possible. Therefore, the triple meter test rhythm contained group sizes identical to that of duple meter habituation rhythms (triple meter, duple grouping), while the duple meter test rhythm had grouping structure identical to that of triple meter habituation rhythms (duple meter, triple grouping). Both test rhythms are presented in Fig. 6 (bottom).

As explained above, certain group sizes created metrical ambiguity, such as groups of three in triple meter. Fig. 7 presents the proportion of events and accents at

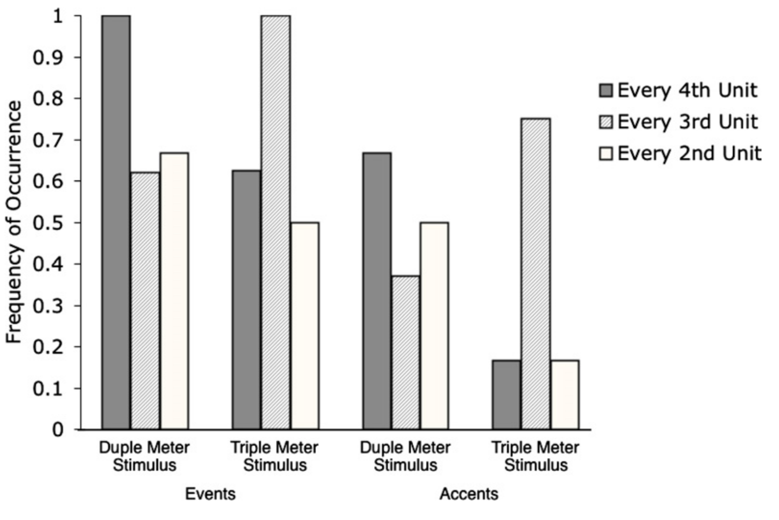

Fig. 7. The average proportion of event and accent occurrence for rhythms used in the test phase of Experiment 2.

potential downbeat positions in each triple and duple meter test rhythm. Compared to the stimuli from Experiment 1, these triple and duple meter rhythms are not as strongly differentiated by frequency of event or accent occurrence. It is important to point out, however, that rhythms need not provide perfect information to imply one meter or the other. Because meter is inferred from probabilistic information, some ambiguity should be tolerable if, overall, a rhythm is consistent with a particular meter. A real world example is *syncopation*, a phenomenon in which events and accents occur "off" the beat, creating tension but not disrupting the perception of meter altogether, especially once listeners have inferred a metrical framework (Clarke, 1999).

Thus, each test rhythm presented features that were both novel and familiar relative to habituation rhythms. One stimulus presented a novel grouping structure but a familiar implied meter, while the other presented a familiar grouping structure but a novel implied meter.

3.1.3. Apparatus and procedure

The apparatus and procedure were identical to Experiment 1 with the following exceptions. During the habituation phase, infants were presented with a series of three of the rhythms used in Experiment 1, all in the same meter (see Fig. 3). Immediately following the habituation phase, infants were presented with two novel test rhythms, one with familiar grouping/novel meter and the other with novel grouping/familiar meter. As in Experiment 1, the meter of habituation rhythms and for the order of test trials was counter-balanced.

3.2. Results and discussion

Infants oriented longer to presentation of post-habituation test rhythms that implied a novel meter and familiar grouping structure than to rhythms that implied a familiar meter and novel grouping structure (raw looking time data are presented in Fig. 8). A three-way ANOVA, with test condition (novel meter/familiar grouping vs. familiar meter/novel grouping, within subjects), habituation condition (triple vs. duple meter, between subjects), and test order (novel meter first vs. familiar meter first, between subjects), revealed a significant main effect of test condition, $F(1,20) = 4.41$, $p < .05$. There were no other significant main effects or interactions with habituation condition or test order.

This result indicates that infants categorized rhythms on the basis of implied meter and not on the basis of grouping structure. If infants had responded to novel grouping structure in Experiment 1, they should have also shown a preference for novel grouping structure in Experiment 2. However, they showed a preference for the familiar grouping structure and the novel metrical structure. Moreover, because we used infant-controlled habituation, we can be confident that the results obtained in both Experiments 1 and 2 reflect a novelty preference (Horowitz, Paden, Bhana, & Self, 1972). In the Experiment 2, test stimuli each presented a different type of novel structure, allowing us to determine which aspect of habituation rhythms dominated infant perception. We can thus conclude that infants we observed in Experiments 1

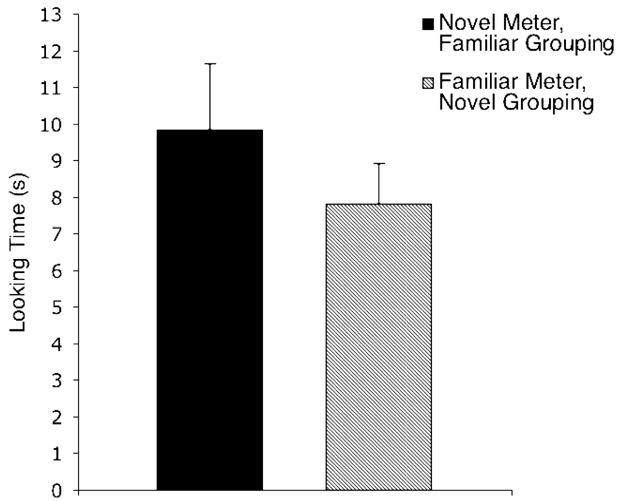

Fig. 8. Mean looking times after habituation (in seconds). Error bars indicate standard errors. Infants looked longer during presentation of the rhythm that implied a novel meter but a familiar grouping structure.

and 2 inferred the underlying meter from the distribution of events and accents in the set of habituation rhythms and not from common grouping structure. Combined, the first two experiments provide the strongest evidence to date that infants can infer metrical structure from rhythmic patterns.

Our findings suggest that infants can perceive meter even though they are not yet capable of producing precisely timed movements in synchrony with music. These results are surprising because they may document a precocious grasp of hierarchical temporal structure relative to hierarchical pitch structure in music, which is not grasped until late childhood (Krumhansl & Keil, 1982; Trainor & Trehub, 1994; Wilson, Wales, & Pattison, 1997). This ability raises questions about the potential functions of metrical structure. Periodic temporal structures could function to draw attention to particular events or relationships between events, thus forming a basis for learning about pitch relations in music (Jones, 1990). It is possible that early abilities for perceiving meter might guide infant attention, enabling infants to interpret and organize incoming musical information. Just as stress facilitates learning of phonotactic cues in speech segmentation, meter might facilitate infants' learning of the complex and hierarchical pitch structures in music.

Tonality, sometimes called the "syntax" of music, refers to the hierarchical system of pitch relations in Western music, specifying concepts of *scale*, *chord*, and *key* at successive hierarchical levels (Cuddy & Badertscher, 1987; Patel, 2003). A large body of evidence suggests that adults possess tacit knowledge of tonality, which allows them to perceive the relative prominence of pitches and to detect "sour" notes in conventional musical contexts (Krumhansl, 1990). Individuals likely acquire this knowledge some time after infancy, as shown by striking differences between infant and adult performance on tasks measuring sensitivity to scale structure (Lynch, Eilers, Oller, & Urbano, 1990), chords (Trehub, Cohen, Thorpe, & Morrongiello, 1986), and key (Trainor & Trehub, 1992). Very little is known about how individuals acquire tonal knowledge, but some evidence suggests that frequency of occurrence and final note position can determine adults' inferences of which pitches are prominent in an unfamiliar pitch system (Creel & Newport, 2002).

Music theorists have asserted that structurally important events occur more frequently metrically strong positions (Meyer, 1973). This hypothesis has been supported by some empirical findings. An analysis of errors by adult and child pianists revealed that notes at strong metrical positions were more likely to be replaced with notes from other strong metrical positions than with notes from weak positions, suggesting that pianists conceptualize pitches according to their position in the meter (Palmer & Pfordresher, 2003). An analysis of jazz improvisations showed that musicians tended to play structurally important notes at metrically strong locations (Järvinen & Toiviainen, 2000). These findings lend support to the proposal that metrical structure, by emphasizing some pitches over others, might serve as a cue for learning complex aspects of pitch structure such as tonality. If meter facilitates infants' learning of hierarchical pitch relations in music, infants should be able to learn an association between strong vs. weak metrical positions and the pitches that tend to occur at those positions.

4. Experiment 3

A final experiment aimed to investigate one potential function of metrical structure. The design from Experiments 1 and 2 was adapted for use with melodies. We created two *tone distributions* (which we labeled A and B) that differed in the frequency with which certain pitches occurred at metrically strong vs. weak positions. For melodies having tone distribution A, half of the pitches occurred more frequently at metrically strong positions, and the other half of pitches occurred more frequently at metrically weak positions. For melodies having tone distribution B, the opposite set of pitches occurred at strong vs. weak metrical positions. During the habituation phase, infants were presented with a series of melodies having the same tone distribution. During the test phase, they heard two novel melodies having a novel or a familiar tone distribution. In a control condition, infants were presented with non-rhythmic (isochronous) versions of the same melodies. If infants learned to associate certain pitches with metrically strong and/or weak positions, we expected infants in the experimental but not the control group would show a novelty preference for melodies having a novel tone distribution.

4.1. Method

4.1.1. Participants

Forty-eight 7-month-old infants (M age = 213.7 days, SD = 12.8) participated, 24 girls and 24 boys. Five additional infants were observed but not included in the sample due to fussing or interruption during testing. All participants were healthy, full-term infants with no complications during delivery and no reported health or hearing problems.

4.1.2. Stimuli

Sixteen rhythmic melodies were created for the experimental condition, and sixteen isochronous melodies were created for the control condition.

4.1.2.1. Experimental stimuli. For the experimental condition, triple meter rhythmic patterns from Experiment 1 were adapted for use as melodic stimuli. Instead of each tone in the rhythm consisting of a fixed pitch, however, each event was assigned one of six pitch values: C4, D4, E4, F#4, G#4, and A#4. These particular pitches were chosen because they are members of a *whole-tone* scale. Whole-tone scales have pitches that are all equally separated by two semitones. We used the whole-tone scale because it is relatively uncommon in Western music and was unlikely to have been encountered by infants. In addition, whole-tone scales lack the perceptually prominent perfect fifth interval, which if present could potentially bias learning in some conditions and not others.

Tone distributions A and B can be conceptualized as artificial tonalities, differentiated by the frequency with which certain pitches occur at strong vs. weak metrical positions. To create tone distribution A, the six pitches were randomly assigned membership to either a strong or a weak group. Pitches assigned to the strong group occurred at strong metrical positions 90% of the time and at weak positions 10% of the time. The reverse was true of pitches assigned to the weak group, which occurred at strong metrical positions only 10% of the time and at weak positions 90% of the time. The pitch of a given event in a rhythm was determined pseudo-randomly. If an event occurred at a strong metrical position in the rhythm it had a 90% chance of being assigned one of the three pitches in the strong group, and events at weak positions had a 90% chance of being assigned a pitch in the weak group. To create tone distribution B, each pitch's assignment was reversed; pitches in the strong group were switched to the weak group and vice versa. Thus, eight unique melodies were created, four for each tone distribution. Analogous to Experiment 1, three melodies within the same category (tone distribution A, for example) could be presented during the habituation phase, while the fourth melody from that familiar category (distribution A) could be paired with a melody from a novel category (distribution B) during the test phase.

To control for the possibility that melodies would be differentiated by the overall frequency of occurrence for individual pitches or sets of pitches regardless of the meter, each melody had a frequency-matched melodic counterpart with an opposite tone distribution but an identical number of occurrences for each pitch. To illustrate, if pitch D occurred six times in a melody from tone distribution A, its melodic counterpart from tone distribution B also contained six instances of pitch D. The two melodies differed only in the placement of that pitch with respect to the meter, with D occurring most often on strong beats in distribution A but on weak beats in distribution B. Fig. 9 shows the proportion of time each pitch occurred at strong vs. weak

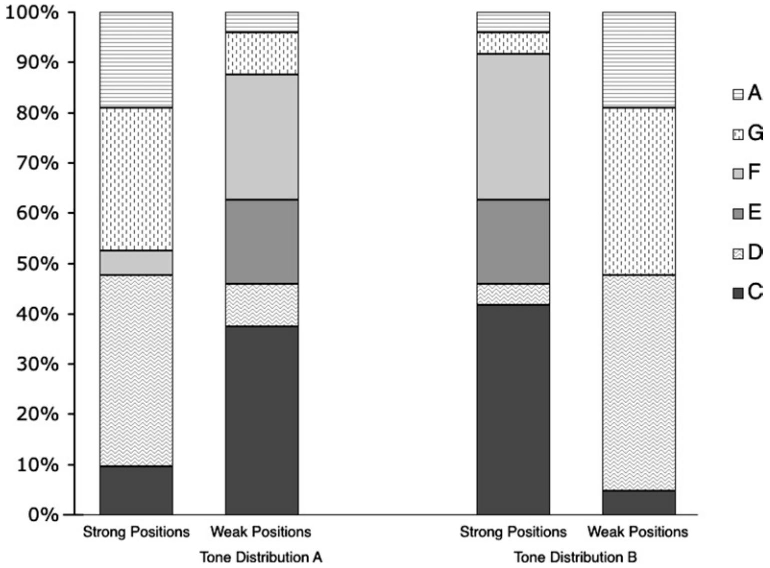

Fig. 9. One pair of frequency-matched melodies from two different tone distributions. Proportions indicate the percentage of time each pitch occurred at strong vs. weak metrical positions in the distributions A and B. In this example, pitches A, G, and D occurred more frequently at strong than at weak metrical positions for tone set A, while they occurred more frequently at weak than at strong positions for tone set B.

metrical positions in two frequency-matched melodies, one with distribution A and one with distribution B. When melodies were presented during the test phase, each melody could thus be presented with its frequency-matched counterpart differing only in its tone distribution.

Assignment of individual pitches to strong vs. weak groups was random, but some configurations might have unintentionally resulted in distinctive melodic features, such as a predominance of rising or falling pitch contours for one tone distribution but not the other. To minimize the possibility of creating such artifacts, we generated each set of tone distributions twice using different *group assignments* as an additional control. For group assignment, pitches D, G#, and A# composed a group (strong in tone distribution A) while pitches C, E, and F# composed the other group (strong in tone distribution B). For the other group assignment, pitches C, E, and G# composed one group (strong in A) while pitches D, F#, and A# composed the other (strong in B).

We assigned pitches to the first 45 events of triple meter rhythms from Experiment 1 to create a total of 16 unique melodies (four melodies with tone distribution A plus four melodies with distribution B, generated twice according to two different group assignments). Each 18 s melody was cycled four times to create a maximum trial duration of 72 s. The timbre, durations, and inter-onset intervals of rhythms were identical to those used in Experiment 1. Although the rhythmic patterns from Experiment 1 contained regular temporal grouping accents, unintended melodic accents in the present stimuli could influence or confuse meter induction (Hannon et al., 2004). To make the meter unambiguous, all trials were preceded by a brief four-cycle drum lead in, which established the primary metrical beat.

4.1.2.2. Isochronous control stimuli. We wanted to rule out the possibility that infants might differentiate test melodies on the basis of sequential regularities in pitch structure, unrelated to meter. We therefore created a set of isochronous melodies for use in a control condition. For each unique melody used in the experimental condition, an isochronous version was created that consisted of an identical sequence of pitches but no rhythmic variation (i.e., no silent units). Control stimuli had 45 isochronous events having a 250 ms inter-onset interval, cycled six times to create a maximum trial duration of 67 s.

4.1.3. Apparatus and procedure

The apparatus and procedure were identical to Experiments 1 and 2 with the following exceptions. The habituation phase consisted of a rotating series of three melodies, all with the same tone distribution. Immediately following the habituation phase, infants were presented with two novel melodies, one with a novel tone distribution and the other with a familiar tone distribution. In the test phase, the melody with the familiar tone distribution was always presented with its frequency-matched counterpart, so individual pitches occurred with equal frequency in both test melodies. Half of the infants were assigned to the experimental condition and half were assigned to the isochronous control condition. Group assignment, habituation condition (tone distribution A or B), and test trial order were counter-balanced.

4.2. Results and discussion

A four-way mixed-design ANOVA, with distribution (novel vs. familiar tone distribution, within subjects), condition (experimental vs. control, between subjects), habituation (habituation to distribution A vs. B, between subjects), and test order (novel vs. familiar distribution first) revealed a significant interaction between distribution and condition, $F(1,40) = 5.213$, $p < .05$. There were no other significant main effects or interactions. Fig. 10 shows that infants in the experimental group looked longer during presentation of post-habituation melodies having a novel vs. familiar tone distribution, while infants in the isochronous control condition showed no preference. Post hoc Bonferroni-corrected *t* tests confirmed a significant novelty preference for infants in the experimental condition, $t(23) = 2.44$, $p < .025$, but no preference in the control condition, $t(23) = .91$, n.s.

This result indicates that infants in the experimental condition learned an association between the metrical structure and the pitch events. We propose that infants learned during habituation that certain pitches were more likely to occur at some metrical positions and not others. This allowed them to differentiate between two post-habituation melodies having novel or familiar pitch distribution properties. Because infants in the control condition were presented with melodies that

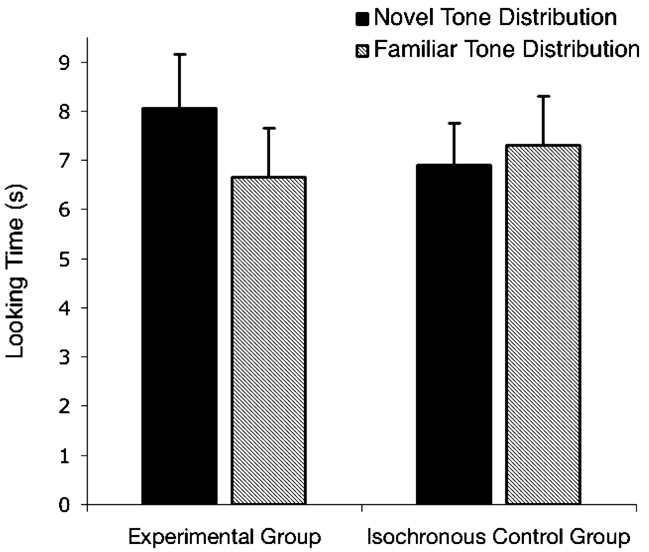

Fig. 10. Mean looking times after habituation (in seconds). Error bars indicate standard errors. Infants in the experimental group looked longer during presentation of melodies having a novel tone distribution than a familiar tone distribution, but infants in the isochronous control condition showed no preference.

were identical in sequential pitch structure but lacking only metrical structure, the absence of a preference in the control condition strongly suggests that the interaction between metrical and pitch structure was responsible for the preference observed in the experimental condition. To our knowledge, these are the first results showing that meter can serve as a framework for infants' learning about properties of pitch structure.

5. General discussion

The present experiments illuminate one way that infants might utilize distributional regularities in auditory input to make sense of complex, rapidly changing auditory patterns such as music. The first two experiments showed that 7-month-old infants categorized unique rhythmic patterns on the basis of underlying metrical structure. Because the rhythms only differed in the frequency of event and accent occurrences at regular periodic positions in the pattern, we can conclude that like adults, infants inferred the meter from these regularities. Experiment 2 further supported this conclusion by pitting two types of structure against each other and showing that implied meter and not grouping structure drove infant preferences. These two experiments provide the most direct evidence to date that infants can infer the underlying meter in rhythmic patterns.

The third experiment revealed one potential function of meter in infancy. Very little is known about how adults acquire knowledge of the complex and hierarchical organization of musical pitch, but some evidence suggests that meter may highlight this structure (Järvinen & Toiviainen, 2000; Palmer & Pfordresher, 2003). We demonstrated that infants are sensitive to contingencies between pitch events and positions within a metrical framework by showing that they responded differentially to sequences in which those contingencies were reversed. The same pitch sequences without metrical structure failed to elicit such a preference, further supporting the notion that associations between pitch and meter were crucial for infant responding. Although these findings suggest that infants can identify associations between pitch and meter, questions remain about whether infants and children can learn about the relative prominence of a pitch from its frequent placement at strong vs. weak positions in the meter. Because adult-like knowledge of tonality in music has not been observed until childhood (Krumhansl & Keil, 1982; Trainor & Trehub, 1992, 1994; Trehub et al., 1986), it is likely that such learning takes place over a period of years. Other types of information likely contribute to structure learning in music, such as individual pitch frequencies (Creel & Newport, 2002; Krumhansl, 1990). A challenge for future research is to examine whether associations between meter and pitch can lead to adult-like perceptions of structural relationships in music.

Overall, our findings indicate that meter is a highly salient structure in the perception of temporal patterns, even for infants. It is currently unknown whether younger infants can perceive meter. It is possible that meter is learned prior to 7 months, through pre- and post-natal exposure to rhythmic patterns and music (Sansavini, 1997). Certainly many aspects of metrical perception are shaped by experience. For example, unlike adults, 6-month-old infants can detect temporal alterations to musical patterns regardless of metrical conventionality (Hannon & Trehub, 2005). This indicates that some culture-specific biases in perceiving meter must be learned between 6 months of age and adulthood. Developmental changes have been observed in synchronized tapping to rhythmic patterns and music, with individuals tapping at an increasingly wide range of slow and fast metrical levels from age 4 to adulthood (Drake, Jones, & Baruch, 2000). Other studies have documented improvement from age 7 to age 9 in classification and discrimination of metrical vs. non-metrical rhythms (Wilson et al., 1997). Individuals may develop more complex temporal representations of meter with a greater number of hierarchical levels as they become increasingly familiar with the musical structures typical of their culture and as their ability to attend to slower metrical levels increases. It is also possible that certain basic aspects of metrical perception arise from a fundamental drive towards synchronization that characterizes the behavior of animate and inanimate systems alike (Strogatz, 2003). Although 7-month-old infants cannot yet coordinate their movements precisely in time, it has been postulated that attentional rhythms can become entrained to external events (Jones & Boltz, 1989; Jones, Moynihan, MacKenzie, & Puente, 2002; Large & Jones, 1999). Infants may easily pick up on periodic regularities in temporal structures they encounter, which makes such regularities a powerful source of information for learning non-temporal information as well as the more complex aspects of temporal structure found in music.

The present findings support a potential function of meter in learning pitch structure, but meter may have other general functions as well. Temporal regularity appears to enhance performance on learning and memory tasks. For example, a regular underlying beat has been shown to improve adults' ability to recall and reproduce rhythmic patterns (Povel & Essens, 1985) and to detect pitch changes (Jones et al., 2002). Highly rhythmic, metrical music facilitates performance on standardized spatial–temporal tasks (Thompson, Schellenberg, & Husain, 2001) and recall of autobiographical details by elderly adults suffering from dementia (Foster & Valentine, 2001). Periodic regularity in speech may also enhance memorization in special cases such as poetry or other oral traditions (Rubin, 1995). Scholars have hypothesized that temporal regularity in caregiver singing and speech may play a fundamental role in regulating infant arousal and enhancing infant learning of linguistic, musical and social information (Stern, Spieker, Barnett, & MacKain, 1983; Trainor et al., 1997). Meter, as one manifestation of periodic temporal structure, may provide important benefits for learning and remembering auditory patterns in general.

A growing body of evidence suggests that general learning mechanisms likely enable infants to detect and utilize distributional regularities for parsing and interpreting complex sequential input. Many of these regularities depend on temporal information, such as simultaneity (e.g., Mattys & Jusczyk, 2001) or temporal proximity (e.g., Kirkham, Slemmer, & Johnson, 2002; Saffran et al., 1996; Thiessen & Saffran, 2003). Infants can even learn to associate units that are temporally non-adjacent (Gomez, 2002; Newport & Aslin, 2004). Our findings are the first to demonstrate that infants can detect temporal regularities that occur periodically. While periodic temporal structure may play only a relatively minor role in the alternating stress patterns of speech, it is fundamental to the temporal structure of music perception and behavior. Meter may thus function as a tool for bootstrapping knowledge about the organization of music, without which individuals could not participate in common musical activities such as listening, dancing, performing, or remembering a familiar tune.

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