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Infant music perception: Domain-general or domain-specific mechanisms?

Sandra E. Trehub [a,*], Erin E. Hannon [b]

[a] *Department of Psychology, University of Toronto at Mississauga, Mississauga, Ont., Canada L5L 1C6*
[b] *Harvard University, USA*

Abstract

We review the literature on infants' perception of pitch and temporal patterns, relating it to comparable research with human adult and non-human listeners. Although there are parallels in relative pitch processing across age and species, there are notable differences. Infants accomplish such tasks with ease, but non-human listeners require extensive training to achieve very modest levels of performance. In general, human listeners process auditory sequences in a holistic manner, and non-human listeners focus on absolute aspects of individual tones. Temporal grouping processes and categorization on the basis of rhythm are evident in non-human listeners and in human infants and adults. Although synchronization to sound patterns is thought to be uniquely human, tapping to music, synchronous firefly flashing, and other cyclic behaviors can be described by similar mathematical principles. We conclude that infants' music perception skills are a product of general perceptual mechanisms that are neither music- nor species-specific. Along with general-purpose mechanisms for the perceptual foundations of music, we suggest unique motivational mechanisms that can account for the perpetuation of musical behavior in all human societies.
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* Corresponding author. Tel.: +1 905 828 5415; fax: +1 905 569 4326.
  E-mail address: sandra.trehub@utoronto.ca (S.E. Trehub).

1. Introduction

In recent years, there has been increasing interest in the biological basis of music (Wallin, Merker, & Brown, 2000; Zatorre & Peretz, 2001) and the possibility of music-specific processing skills (Hauser & McDermott, 2003; Miller, 2000; Peretz & Coltheart, 2003). Some scholars posit ''core mechanisms'' that enable humans, regardless of musical training, to carry a tune, move in time to music, and respond emotionally to music. Peretz and Coltheart (2003) describe these core mechanisms as a system of modules, each of which is dedicated to the analysis or processing of different aspects of music such as melodic contour, intervals, and rhythm. Other scholars contend that a music faculty evolved through natural or sexual selection (Dissanayake, 2000; Hauser & McDermott, 2003; Miller, 2000). They suggest that music-related skills may have enhanced reproductive fitness in ancestral times by strengthening interpersonal relations or group solidarity.

Biological or modular conceptions of music processing stand in sharp contrast to notions of music as frivolous, its structures governed largely by cultural and economic circumstances (Nettl, 1983; Pinker, 1997) rather than by universal processing dispositions or constraints (Trehub, 2000, 2003a). In a now infamous passage, Pinker (1997) characterizes music as ''auditory cheesecake'', with competence in the musical realm dependent on systematic training. He proposes that music evolved as a by-product of other adaptations, without providing unique functional advantages. In the case of language, however, he posits a dedicated neural organ, innate grammatical components, and developing linguistic abilities that unfold naturally without any training (Pinker, 1999).

Although explicit knowledge of music and some kinds of performance may require training, intuitive knowledge of the structural and stylistic features of music results from mere exposure (Smith, Kemler-Nelson, Grohskopf, & Appleton, 1994; Tillmann, Bharucha, & Bigand, 2000). For example, adults typically detect sour notes in familiar musical passages (Drayna, Manichaikul, de Lange, Snieder, & Spector, 2001), and they do so even in unfamiliar passages that conform to the conventions of their musical culture (Cuddy, Cohen, & Mewhort, 1981; Trainor & Trehub, 1992). They recognize and produce a sizable repertoire of popular and traditional songs, and they can tap out musical rhythms (Snyder & Krumhansl, 2001). Moreover, mothers around the world sing to their infants in the course of providing care (Trehub & Trainor, 1998), and the songs they sing have striking cross-cultural similarities (Trehub, Unyk, & Trainor, 1993; Unyk, Trehub, Trainor, & Schellenberg, 1992). In short, musically untrained adults' understanding of musical structure is comparable to that of musical experts (Bigand, 2003).

Proponents of modular accounts of language bolster their case by means of dissociations between various linguistic skills (Ullman et al., 1997) and between linguistic and general cognitive skills (Gopnik, 1997; Pinker, 1999). There are reasons to question the specificity of syndromes such as specific language impairment (Joanisse & Seidenberg, 1998; Norbury, Bishop, & Briscoe, 2002) and Williams

syndrome (Bellugi, Bihrle, Neville, Doherty, & Hernigan, 1989). Deficits have been identified in the "spared" domain for both syndromes, although such deficits are less severe than those in the affected domain (Karmiloff-Smith, Brown, Grice, & Paterson, 2003).

Proponents of modular accounts of music (Peretz & Coltheart, 2003) point to music processing deficits in the context of intact speech processing (Peretz & Hyde, 2003) and speech processing deficits in the context of spared music processing (Hébert, Racette, Gagnon, & Peretz, 2003). Whether the music processing deficit is secondary to neurological damage (Peretz et al., 1994) or primary (no identifiable damage) (Peretz et al., 2002), the presumed underlying problem involves basic pitch processing (Peretz et al., 2002). Such pitch processing difficulties may well have implications for aspects of speech processing such as the differentiation of voices and prosodic variations. In fact, voice recognition problems have been noted in some cases of amusia (Patel, Foxton, & Griffiths, 2005; Peretz et al., 1994).

There is a rich tradition in cognitive science – cognitive neuropsychology, in particular – of interpreting double dissociations (e.g., disordered music processing with spared speech processing, and disordered speech processing with spared music processing) in terms of differentiated mental functions, but there is considerable controversy about the utility of such inferences (Dunn & Kirsner, 2003; Juola & Plunkett, 2000). In principle, comparable (intact) performance in one domain could arise from different processing mechanisms (Deruelle, Mancini, Livet, Casse-Perrot, & de Schonen, 1999). Moreover, patterns of relative strength and weakness may differ dramatically at different phases of life, especially in developmental disorders such as Down syndrome, Williams syndrome, or specific language impairment (Karmiloff-Smith et al., 2003).

A modular account of music processing implies some degree of domain-specific processing and innateness. For Peretz and her associates, adult–infant parallels in music perception reflect innate, domain-specific skills. Alternatively, these parallels could result from perceptual skills that are not exclusive to music or to our species. In effect, modular conceptions invoke a music-specific mode of processing that has much in common with the "special" or linguistic mode of processing that flourished in the 1960s and 1970s (e.g., Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). At that time, 1-month-old infants' categorical perception of stop consonants (Eimas, Siqueland, Jusczyk, & Vigorito, 1971) was interpreted as confirmation that phoneme perception was unlearned, species-specific, and speech-specific. Subsequent findings of categorical perception by chinchillas (Kuhl & Miller, 1975), monkeys (Waters & Wilson, 1976), budgerigars (Dooling, Okanoya, & Brown, 1989), quail (Kluender, 1991), and crickets (Wyttenbach, May, & Hoy, 1996) sparked renewed interest in species-general or auditory accounts of phoneme perception. Thus, it is prudent to remain cautious about music-specific modes of processing until more general accounts have been ruled out. Accordingly, we consider the available literature on infants' perception of pitch and temporal patterns, with comparative perspectives presented, as available.

2. Pitch pattern processing

2.1. Pitch contour

Relational pitch processing is central to the perception and appreciation of music. A tune is defined by its *pitch relations*, without regard to the specific pitch levels of its component tones. For example, adults recognize a familiar tune at any pitch level within the musical range. Infants seem to do likewise. After limited exposure to a melody – as few as three repetitions in some cases – 5- to 10-month-olds treat transpositions of that melody (i.e., alteration of component pitches but pitch relations preserved) as familiar, or equivalent to the original melody (Chang & Trehub, 1977a; Trehub, Bull, & Thorpe, 1984; Trehub, Thorpe, & Morrongiello, 1987). When the internal tones are reordered (Trehub et al., 1984) or a single tone is changed (Trehub, Thorpe, & Morrongiello, 1985), infants treat the resulting melody as novel, especially when the change alters the melodic, or pitch, contour (i.e., pattern of rising and falling pitches). Pitch contour is the most salient aspect of a melody for infant listeners, who detect contour changes even when the standard and comparison melodies are separated by 15 s (Chang & Trehub, 1977a) or by sequences of irrelevant tones (Trehub et al., 1984). Fig. 1 depicts three transformations of the tune ''Happy Birthday'': a transposition (perceived as ''same'' by infants and adults), a
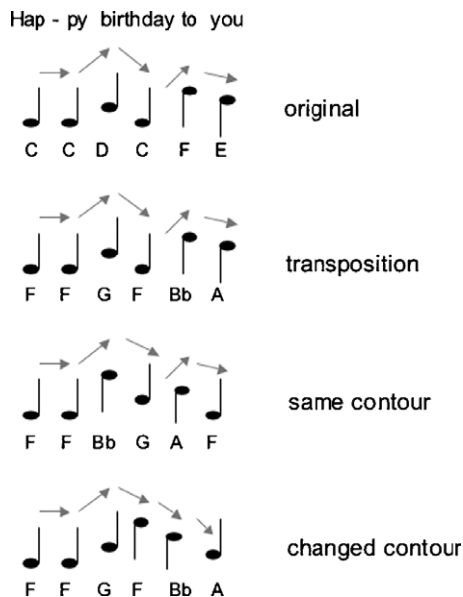

Fig. 1. Relative pitch structure in melodies. Individual notes are assigned conventional pitch names (A B C), and arrows indicate the melodic direction. The tune, ''Happy Birthday'' (original) can be presented at a new pitch level (transposition), or one or more intervals can be changed in a way that preserves the original contour (same contour) or changes it (changed contour).

same-contour variation (perceived as "same" if unfamiliar and as "different" if familiar), and a changed-contour variation (perceived as "different").

The salience of pitch contour is not restricted to the musical domain. According to Fernald (1991), pitch contour is the most salient aspect of infant-directed speech. Maternal utterances that express approval, comfort, or prohibition to prelinguistic infants have common pitch contours across a number of languages. Moreover, pitch contours are thought to underlie infants' enhanced responsiveness to the maternal speech register (Fernald & Kuhl, 1987).

2.2. Intervals

Adults' ability to recognize or reproduce familiar tunes necessarily depends on their encoding of finer pitch relations, specifically, intervals, or precise pitch distances between successive tones. In the context of novel melodies, however, adults often retain global contour information rather than detailed interval information (Bartlett & Dowling, 1980). If infants' encoding of pitch patterns were restricted to pitch contour, then they would be unable to differentiate any melodies that shared the same contour. Infants often confuse same-contour melodies (e.g., Trehub et al., 1987; Trehub, Thorpe, & Trainor, 1990), but they can detect subtle interval changes when the melodies obey certain "rules". For example, when the component tones of a pattern are related by small-integer ratios, as in the prototypical major triad (e.g., C-E-G-E-C; ratios of 4:5:6), infants detect a one-semitone change (e.g., G to G#, or G to F#), even if the standard and comparison melodies are presented at different pitch levels (Cohen, Thorpe, & Trehub, 1987; Trainor & Trehub, 1993b). By contrast, they fail to detect a comparable interval change in a melody with the same rising–falling contour (C-E-G#-E-C) if the tones are related by large-integer ratios (16:20:25) (Cohen et al., 1987; Trainor & Trehub, 1993b).

2.3. Consonance and dissonance

Infants' success or failure at detecting interval changes depends on the nature of the intervals. For example, 9-month-old infants can detect changes in a sequence of repeating intervals if those intervals are consonant but not if they are dissonant (Schellenberg & Trehub, 1996b). Consonant intervals, or those with small-integer ratios (3:2, or pitch difference of seven semitones; 4:3, or pitch difference of five semitones), are more readily encoded by infant, child, and adult listeners than are dissonant intervals, or those with large-interval ratios (45:32, or pitch difference of six semitones) (Schellenberg & Trehub, 1994, 1996a, 1996b; Trainor, 1997). Infants also categorize intervals of varying magnitude on the basis of their consonance or dissonance (Schellenberg & Trainor, 1996).

Small-integer frequency ratios in sequential or simultaneous tone patterns are ubiquitous in Western tonal music, which may account for enhanced processing of such intervals in adulthood and infancy. Infants' sensitivity to statistical regularities in tone sequences (Saffran, Johnson, Aslin, & Newport, 1999) adds plausibility to an experiential account. In principle, familiarity with consonant harmonic intervals

could arise from exposure to the simultaneous components of speech sounds (Ter-hardt, 1974), and familiarity with consonant melodic (sequential) intervals from pre-natal and postnatal exposure to ambient music (Hauser & McDermott, 2003). An alternative explanation, which is consistent with the available cross-cultural and cross-species evidence, implicates inherent processing biases for consonant intervals (Schellenberg & Trehub, 1996b; Trehub, 2000). Octaves (2:1 ratio), perfect fifths (3:2 ratio), and logarithmic pitch scales have played a structurally important role in musi-cal systems across cultures and historical periods (Dowling & Harwood, 1986; Kil-mer, Crocker, & Brown, 1976; Sachs, 1943). The selection of similar (consonant) musical intervals across cultures parallels the selection of similar speech sounds, cat-egory boundaries, and sequencing constraints across cultures on the basis of their relative ease of processing (Comrie, 1981; Locke, 1990; Maddieson, 1984).

Differential processing of consonant and dissonant intervals is not limited to human listeners. After European starlings are trained to respond differentially to a single consonant and dissonant chord, they generalize those responses to other con-sonant and dissonant chords, raising the possibility that they and other non-human species are sensitive to acoustic features that distinguish consonance from dissonance (Hulse, Bernard, & Braaten, 1995). Processing differences may not implicate listening preferences, but they do in the case of human listeners. When 2-, 4-, and 6-month-old infants are given the opportunity of listening to patterns of consonant or dissonant intervals, they listen less and exhibit increased negative affect during presentations of the dissonant intervals (Trainor, Tsang, & Cheung, 2002; Trainor & Heinmiller, 1998; Zentner & Kagan, 1996). Their preferences parallel those of adults, who typ-ically avoid dissonant music (Meyer, 1994). By contrast, cotton-top tamarins show no such preferences for consonant intervals (McDermott & Hauser, 2004). When given a choice between music and silence, tamarins opt for the latter (McDermott, 2005), which confirms their disinterest in music. McDermott and Hauser (2004) emphasize the substantial differences between human and tamarin musical preferenc-es, in contrast to their similarities in speech perception (Newport, Hauser, Spaepen, & Aslin, 2004; Ramus, Hauser, Miller, Morris, & Mehler, 2000). They suggest that the human preference for consonance arises from a music-specific adaptation. It is important to note, however, that despite numerous cross-species parallels in speech discrimination and categorization (Sinnott, 1994), no cross-species parallels in speech preferences have been identified to date, highlighting the distinction between perceptual skills and preferences. Thus, cross-species differences may reflect motiva-tional factors rather than perceptual adaptations.

2.4. Absolute and relative pitch

Relative pitch processing, which is indispensable for the enjoyment of music as we know it, is thought to be restricted to human listeners. Over the years, numerous attempts to demonstrate relational pitch processing in non-human species have failed, with rats, starlings, budgerigars, and monkeys discriminating tunes by means of any available absolute cue rather than the relative pitch cues that are so prominent to human listeners (D'Amato, 1988; Hulse & Cynx, 1985).

In an intriguing study of rhesus monkeys, Wright and his associates challenged the prevailing wisdom about relational pitch processing in non-human listeners (Wright, Rivera, Hulse, Shyan, & Neiworth, 2000). First, they spent months training two monkeys on the daunting task of judging pairs of tone sequences, or melodies, as either same or different. Success on this task required two things: (1) perceiving the melodies as configurations or gestalts based on their pitch relations, and (2) recognizing the same configurations at different pitch levels. One question of interest was whether monkeys would consider transposed melodies as equivalent (''same''). If they did so, would they generalize this response to melodies transposed by one or two octaves (2:1 ratio) and to melodies transposed by .5 or 1.5 octaves (45:32 ratio)? For tunes consisting of randomly generated tones, the monkeys responded to all transpositions as ''different''. For those based on simple children's songs (e.g., ''Old MacDonald'', ''London Bridge'', ''Happy Birthday'') or on the compositional rules of Western tonal music, monkeys responded to one- and two-octave transpositions as ''same'' and to the other transpositions as ''different''. Thus, monkeys treated octave transpositions as equivalent, just as human adults and infants do (Burns, 1999; Demany & Armand, 1984). These findings indicate some similarity between the relative pitch processing abilities of non-human listeners and those of human infants, who also have difficulty with atonal patterns or those that violate universal musical constraints (Trehub, Schellenberg, & Hill, 1997). Adults and infants also respond differently to different types of transpositions. For example, they have significantly greater difficulty recognizing a melody when it is transposed to a musically unrelated key (e.g., six-semitone change, or 45:32 ratio) than to a related key (e.g., seven-semitone change, or 3:2 ratio) (Trainor & Trehub, 1993a).

In a more recent study, two rhesus monkeys learned to differentiate ascending from descending tone sequences in the context of variations in pitch level (Brosch, Selezneva, Bucks, & Scheich, 2004). Note, however, that success on this relational pitch task required 199 training sessions for one monkey and 211 for the other because of their *preference* for responding to the absolute pitch of individual tones. Whether consonant tone relations would accelerate the course of learning remains to be determined.

Just as monkeys (Brosch et al., 2004; Wright et al., 2000) and other species (Mac-Dougall-Shackleton & Hulse, 1996) can respond to relative pitch information in some circumstances, human listeners may be capable of responding to absolute pitch information with suitable tasks and materials. Characterizations of adults' pitch memory as poor arise primarily from studies using isolated tones (Ward, 1999). When familiar materials are used, the findings differ dramatically. For example, college students not only recognize the tunes that accompany television programs that they watch regularly, but they also remember their pitch level (Schellenberg & Trehub, 2003). When they hear two excerpts of instrumental theme music from these programs, one of which is pitch-shifted by one or two semitones, they can identify the original version. Similarly, their sung renditions of popular songs are generally within two semitones of the canonical recording (Levitin, 1994). Mothers exhibit even greater uniformity in their repeated performances of songs to infants, which are often identical in pitch level (Bergeson & Trehub, 2002).

Although absolute pitch processing may be advantageous for infant listeners, supporting maternal voice identification, for example, the available evidence is largely consistent with relative pitch processing (Trainor, 2005; Trehub, 2000, 2003b). Saffran (2003) offers an alternative perspective based on evidence from statistical learning tasks. On such tasks, infants receive 2 min of uninterrupted exposure to a continuous sequence of equal-duration tones, after which they are tested on their recognition of a three-tone fragment that occurred more frequently than other three-tone fragments in the longer sequence. When absolute and relative pitch cues are available, infants accord priority to the absolute pitch cues, whether the component tones of the original sequence are selected randomly (Saffran & Griepentrog, 2001) or from the C-major scale (Saffran, 2003). When absolute cues to the three-tone fragments are uninformative, infants learn on the basis of relative pitch cues (Saffran, Reeck, Niebuhr, & Wilson, 2005) in these musically impoverished tone sequences.

Other investigators have explored absolute and relative pitch processing in long-term memory. After 1 week of brief daily exposure to a synthesized piano rendition of an initially unfamiliar folk song, 6-month-olds listen longer to a novel folk tune than to the original (Trainor, Wu, & Tsang, 2004) – which implicates relative pitch processing – but they exhibit no differential responding to the familiar tune at a novel pitch level or at the original pitch level (Plantinga & Trainor, 2005). Plantinga and Trainor (2005) argue that absolute pitch information may not be salient or memorable for infants. Alternatively, infants may encode less detail from synthesized instrumental melodies than from ecologically valid materials such as expressive vocal performances. When 7-month-olds are exposed to a soothing vocal performance of a lullaby in a foreign language (Russian, German, or Spanish) for brief daily sessions over the course of 2 weeks, they subsequently listen longer to a rendition sung at a higher or lower pitch level relative to the original rendition (Volkova, 2004), which indicates their retention of absolute features of the original performance. Thus, absolute and relative pitch processing strategies may depend as much on the nature of the task and musical materials as on the age and species of the listener (Trehub, 2003b). Language environment may also play a role. Some investigators contend that early exposure to a tone language has long-term implications for pitch memory (Deutsch, Henthorn, Marvin, & Xu, 2004).

2.5. Adult–infant comparisons

How do the pitch processing capabilities of infants differ from those of adults? Adult–infant similarities, such as those involving contour (Trehub et al., 1984, 1987) and interval processing (Schellenberg & Trehub, 1996b), may reflect innate processing constraints that have influenced the selection of pitch material (scales and intervals) across musical cultures (Trehub, 2000; Trehub et al., 1997). Although adult–infant parallels could arise from very early exposure to music, that is unlikely to be the case. For one thing, musical exposure in early infancy cannot account for the documented differences between adults and infants, which highlight aspects of musical processing that necessarily depend on culture-specific exposure. Adults, for example, readily detect a changed note that disrupts the key of the original

melody, but they often fail to detect changes that are consistent with the key and harmonic implications (Trainor & Trehub, 1992). By contrast, infants perform equivalently on both types of change (Trainor & Trehub, 1992). In effect, they outperform adults on the contextually appropriate change because of their lack of culture-specific tonal knowledge. Several years of incidental exposure seem to be necessary for adult-like understanding of tonality (Cuddy & Badertscher, 1987; Krumhansl & Keil, 1982; Lamont & Cross, 1994; Trainor & Trehub, 1994). Thus, although it is generally the case that long-term exposure to music leads to greater specificity in the registration of contour and interval information (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004), musical knowledge occasionally interferes with the encoding of pitch relations, especially when the relations are unfamiliar or unconventional (Lynch, Eilers, Oller, & Urbano, 1990; Schellenberg & Trehub, 1999; Trehub, Schellenberg, & Kamenetsky, 1999).

Infants' failure to encode pitch sequences in terms of the tonal framework of their culture is superficially similar to the tonal processing difficulties of amusic individuals (Peretz, 1993), but infants' failure stems from insufficient opportunity to internalize that framework. Infants differ from amusic individuals in most other respects. They experience musical patterns as coherent (Trehub et al., 1987); they exhibit sensitivity to consonance and dissonance (Schellenberg & Trehub, 1996b); they enjoy listening to music, especially vocal music (Nakata & Trehub, 2004); and they remember realistic musical material for long periods (Saffran, Loman, & Robertson, 2000; Trainor et al., 2004).

To what extent are infants' pitch processing skills species-general or species-specific? We have identified parallels in pitch processing on the part of human infants and non-human listeners, which imply species-generality. It is important to note, however, that test procedures are very different across species. Most infant procedures offer secondary rewards (e.g., visual displays) or no rewards, and the data are gathered in a single 5- or 10-min session that may include an exposure or training phase as well as a test phase. This situation contrasts markedly with typical test scenarios for non-human listeners, which feature adult animals, primary rewards (e.g., food, water) and hundreds or thousands of training trials distributed over days or months. Because of the difficulty of enticing human infants to do what they are not inclined to do, the available data probably underestimate their abilities. From the limited cross-species evidence, it is reasonable to conclude that the differences are primarily attentional and motivational rather than perceptual. Such initial differences may lead to increasingly divergent pitch processing outcomes over the course of human development.

3. Temporal pattern processing

Because music unfolds over time, as speech does, its processing necessarily depends on adequate temporal abilities. Listeners must segment the input into meaningful chunks or units, detect relations among those units, and anticipate future events. Three aspects of temporal organization are fundamental to the perception

of music: grouping, rhythm, and meter. *Grouping* refers to the perception of boundaries between groups and subgroups of elements in an unfolding musical sequence. *Rhythm* refers to the pattern of temporal intervals in a sequence. Although rhythmic patterns may be *isochronous*, consisting of a single repeating temporal interval, music typically incorporates a range of interval sizes. *Meter* refers to the abstract, hierarchical structure of music, which is experienced as a strong and weak alternation of "beats". Although grouping, rhythm, and meter can influence each other, they are nevertheless distinct aspects of temporal structure in music (Lerdahl & Jackendoff, 1983). Our contention is that infants begin life with basic abilities that are useful for perceiving these kinds of temporal structures.

3.1. Grouping

Listeners rarely experience a musical stimulus as a series of unrelated pitches or sounds. Instead, they segment complex patterns into groups and subgroups of events. Adults are biased to group successive events according to their similarity in spectral structure (timbre), pitch, intensity, temporal proximity, or spatial location. For example, they segment a repeating, ambiguous pattern into groups of similar elements, reporting XXXOO or OOXXX, which begin and end with multiple instances of the same element (X or O) but rarely reporting OXXOO, which cuts across multiple identical elements (O) (Royer & Garner, 1966). Adults judge the similarity or difference of two sequences more quickly and accurately if the sequences begin at preferred starting points (Royer & Garner, 1966). In addition to element similarity, adults use other cues to assign boundaries, including falling pitch, increased duration, and sudden changes in intensity, timbre, melodic contour, or harmonic stress (Palmer & Krumhansl, 1987). Fig. 2 depicts temporal grouping for a well-known song. Note that the elements in this example are grouped by pitch similarity and increased duration.

One consequence of grouping processes is that sensitivity to temporal changes *between* groups is poorer than sensitivity to changes *within* groups. For example, adults are less likely to notice small gaps between groups differing in pitch (e.g., HHH LLL for high and low) or timbre (PPP VVV, for piano and violin) than identically sized gaps within those groups (e.g., HH HLLL) (Fitzgibbons, Pollatsek, & Thomas, 1974; Thorpe, Trehub, Morrongiello, & Bull, 1988). These processes also operate in the context of complex musical patterns. For example, listeners have greater difficulty detecting a pause between musical phrases than a pause within a phrase (Repp, 1992b). Because adults are sensitive to duration cues that mark group
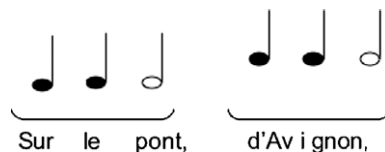

Fig. 2. Temporal grouping of French song "Sur Le Pont D'Avignon".

boundaries, they may anticipate a pause at such locations and therefore fail to notice one if it occurs.

Infants and children also group patterns on the basis of similarity in pitch, loudness, or timbre. For example, 6- and 8-month-old infants and 5-year-old children have greater difficulty detecting small timing changes between tone groups than within tone groups (Thorpe & Trehub, 1989; Thorpe et al., 1988). Infants are also sensitive to cues associated with musical phrase boundaries, such as falling pitch intervals and phrase-final lengthening. For example, 8-month-olds are less accurate at detecting small pauses after long-duration notes than after short-duration notes in a melody, which implies that the longer notes mark group boundaries (Trainor & Adams, 2000). Moreover, 4- to 6-month-olds listen longer to versions of a Mozart minuet that has pauses inserted between musical phrases rather than within phrases (Krumhansl & Jusczyk, 1990), but only when the phrase boundaries are marked by falling pitch and lengthened note duration (Jusczyk & Krumhansl, 1993). Thus, infants group patterns according to the similarity of component elements, and they have expectations about which events are likely to occur at musical phrase boundaries.

Parallels in the temporal grouping biases of infants and adults may implicate domain-general or music-specific abilities. To what extent do such grouping biases operate outside of music? Falling pitch and increased duration play a role in infants' perception of word and phrase boundaries. For example, prelinguistic infants listen preferentially to speech samples with pauses inserted between rather than within verbal phrases (Kemler-Nelson, Hirsh-Pasek, Jusczyk, & Wright-Cassidy, 1989). They also show preferences for pauses between rather than within words (Echols, Crowhurst, & Childers, 1997; Myers et al., 1996). Because falling pitch and increased duration are exaggerated in infant-directed speech (Fernald, 1991), these cues are likely to facilitate infants' segmentation of speech as well as music.

Are such temporal grouping processes limited to human listeners, or is their applicability more general? The available evidence favors generality. After starlings are trained to respond differentially to auditory patterns such as XXXXXOO versus OXOXOOXX, discriminative responding continues under transformations that alter the identity of individual elements (e.g., pitch, timbre) but preserve the grouping structure (Braaten & Hulse, 1993). This evidence implies that temporal grouping processes are not species-specific, although music-specific processes could arise in humans from extended exposure to the hierarchical grouping structures in complex pieces of music.

3.2. Rhythm

Musical patterns typically contain multiple temporal intervals of different durations. By encoding the relative size, or duration, of such intervals, listeners can remember and reproduce familiar melodies or rhythmic patterns. For example, the well-known ''shave and a haircut'' rhythm, shown in Fig. 3, is recognized from its characteristic pattern of temporal intervals (long-short-shortest-long-longest-long-long). It remains recognizable despite changes in tempo (rate), timbre (e.g., clapping,
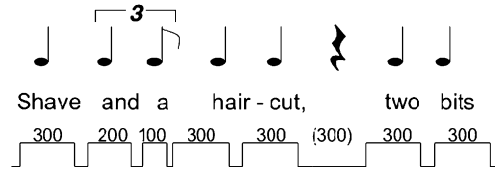
Fig. 3. Rhythmic pattern, presented in music notation and iconically as event durations (in milliseconds).

humming), and pitch level (e.g., high, low) as long as the ratios between temporal intervals are preserved.

Like adults, infants use the relative size and order of temporal durations to discriminate rhythmic patterns. After 2-month-old infants habituate to a specific rhythmic structure (600–100–300 ms), they show increased interest in a novel arrangement of the same temporal intervals (100–600–300 ms) (Demany, McKenzie, & Vurpillot, 1977). Similarly, after 4- to 10-month-olds habituate to one rhythm (2–2 grouping), they show response recovery to a novel arrangement (3–1 grouping) of the same elements (Chang & Trehub, 1977b; Lewkowicz, 2003). Infants seem to encode rhythmic patterns on the basis of relative duration, as reflected in their ability to categorize different instances of the same basic rhythm. For example, infants detect changes to a rhythm, regardless of concurrent variations in frequency and tempo (Trehub & Thorpe, 1989). They also recognize transformations of a rhythmic pattern across sensory modalities. After 4-month-olds listen to an audio recording of a repeating syllable in a 2–2 or 3–1 rhythm, they exhibit preferential responding to a silent visual display that matches the familiarized rhythm (Mendelson, 1986).

Overall, these results imply that infants, like adults, respond primarily to patterns of relative duration, not to isolated temporal intervals. Nevertheless, they also detect changes in absolute temporal structure. For example, infants show renewed interest in a familiar rhythm when it is presented at a new tempo (Pickens & Bahrick, 1995), and they sometimes confuse novel and familiar rhythms when both undergo substantial tempo changes (Pickens & Bahrick, 1997). Nevertheless, relative temporal structure may become increasingly salient with age or experience (Morrongiello, 1984).

Is the perception of relative temporal information unique to music? Although structured sequences of temporal intervals are not fundamental to the organization of speech, speech is rhythmic in the sense that it unfolds over time and contains temporal units of varying duration. Linguists classify languages on the basis of their rhythmic organization. The classification criteria are not entirely clear, but recent work indicates that variability in vowel and consonant durations can be used to group languages into rhythmic classes (Ramus, Nespor, & Mehler, 1999). Infants seem to perceive the rhythms of speech early in life. For example, French newborns distinguish speech samples from different rhythmic classes, such as English and Japanese, but not those within the same rhythmic class, such as English and Dutch (Nazzi, Bertoncini, & Mehler, 1998). Infants' ability to discriminate words differing only in vowel duration (Eilers, Bull, Oller, & Lewis, 1984) may enable them to use such duration cues to differentiate languages.

Measures of durational contrast in English and French are associated with culture-specific rhythms in music from England and France, which implies that rhythmic structures in speech influence, or are influenced by, rhythmic structures in music (Patel & Daniele, 2003). Thus, although rhythmic structure in speech differs from that found in music, the ability to perceive relative duration is essential to both domains.

Non-human animals perceive some aspects of rhythmic structure. For example, pigeons categorize temporal intervals on the basis of relative duration (longer or shorter) (Zentall, Weaver, & Clement, 2004), and starlings (Hulse, Humpal, & Cynx, 1984a) as well as bottle-nosed dolphins (Harley et al., 2003) discriminate contrasting rhythms composed of identical intervals. After starlings learn to respond differentially to rhythmic versus arrhythmic patterns, they show generalization to patterns with altered tempo and tone frequency (Hulse, Humpal, & Cynx, 1984b). Dolphins also discriminate rhythms despite transformations of pitch level and tempo (Harley et al., 2003). These findings imply that rhythmic patterns are salient for non-human as well as human listeners.

3.3. Meter

The pattern of durations in a sequence determines the rhythm, but meter must be inferred from periodic regularities in the music. Most listeners experience meter as an underlying pattern of strong and weak isochronous beats, along with one or two faster or slower isochronous patterns that subdivide or multiply the base interval of the primary beat. Fig. 4 depicts two common meters, duple and triple, along with two beat levels and the patterning of strong and weak events. Meter enables individuals in a group to synchronize their movements in dancing, marching, tapping, clapping, and singing. Meter is also thought to guide listeners' attention dynamically, enhancing the anticipation of future events (Jones & Boltz, 1989).
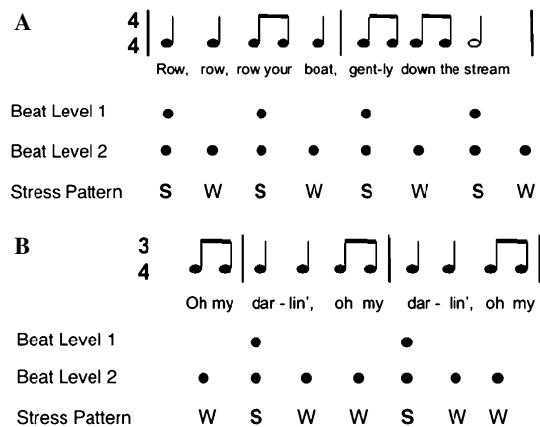

Fig. 4. Duple (A) and triple (B) metrical hierarchies for two popular songs.

The occurrence of synchronized dancing, tapping, and other types of rhythmic behavior across cultures and historical periods attests to the relative ease of discerning the metrical structure in most music. When adults are asked to tap to music, they show a high degree of inter-subject agreement, tapping at metrically strong beats in the music (Drake, Penel, & Bigand, 2000; Snyder & Krumhansl, 2001). Analyses of musical corpora reveal that events occur more frequently at strong than at weak metrical positions in Western classical music (Palmer & Krumhansl, 1990) and children's nursery tunes (Palmer & Pfordresher, 2003), which indicates that frequency-of-event occurrence is an important cue to meter. The periodic occurrence of accents also induces meter. Accents arise when events are perceptually salient by virtue of their loudness, duration, high pitch, or location (e.g., melodic peaks, group boundaries). Accents predict strong metrical positions in written music (Huron & Royal, 1996; Large & Kolen, 1994), tapping positions (Snyder & Krumhansl, 2001), and meter identification (Hannon, Snyder, Eerola, & Krumhansl, 2004). The distribution of events and accents helps listeners converge on similar metrical interpretations, but metrical interpretations sometimes emerge in the absence of such cues. For example, the tendency to perceive meter is so strong that most listeners perceive a "tick-tock" or strong–weak pattern in isochronous patterns of uniform tones (Brochard, Abecasis, Potter, Ragot, & Drake, 2003).

Metrical information may be salient to infants, who are often rocked and bounced in time to music. When mothers sing to infants, they exaggerate the conventional duration and loudness of elements at strong metrical positions (Trainor, Clark, Huntley, & Adams, 1997). Subtle changes in duration and loudness are detectable to 10-month-olds, who distinguish otherwise identical musical patterns on the basis of the performer's intended meter (Palmer, Jungers, & Jusczyk, 2001). Moreover, infants categorize rhythmic patterns on the basis of a common underlying meter. After 7-month-old infants are familiarized with a set of three unique rhythms that induce the same meter, they listen longer to a novel rhythm that induces a novel meter than to a novel rhythm that induces the familiar meter (Hannon & Johnson, 2005). Infants also use movement cues to infer meter. When 7-month-old infants are bounced to an ambiguous rhythm in accordance with one of two possible meters, they show a subsequent preference for a version of the rhythm in which loudness accents match the original bouncing meter (Phillips-Silver & Trainor, 2005). Infants who merely watch the experimenter's bouncing activity show no such preference. Thus, infants can infer meter from auditory patterns alone or from combined auditory and movement cues.

Synchronized movement to music has been observed in all known cultures, which implies that this skill is universal and perhaps unique to human musical behavior (Brown, 2003). Questions about the relevance of meter to non-musical domains are controversial. Speech is thought to have isochronous inter-syllable or inter-stress intervals (Lehiste, 1977), but this view is not supported by acoustic analyses of natural speech (Ramus et al., 1999). Nevertheless, listeners may perceive isochrony in the absence of measurable isochrony (Lehiste, 1977), just as they do in music. To illustrate, inter-onset intervals in musical performances are not strictly isochronous, but vary as a function of the performer's expressive intentions (Repp, 1992a).

However, this variation does not preclude the perception of a regular, isochronous beat. Whether meter is restricted to music or has functions beyond music must await direct comparisons of perceived and produced isochrony in music and speech.

There are no known examples of non-human animals synchronizing their behavior to music, which makes it tempting to suggest that musical meter is species-specific. The closest non-human parallel to musical meter is the synchronous flashing of fireflies. Some firefly species synchronize their flashing with that of other fireflies and with flashing artificial lights, typically in the context of courtship (Buck, 1988). Interestingly, some species synchronize at multiples of an exogenous stimulus, an ability that is characteristic of human responses to musical meter (Buck, 1988). Different mechanisms may underlie firefly flashing and human dancing, but similar mathematical principles can describe and predict synchronization in firefly flashing, human tapping, sleep–wake cycles, menstrual cycles, and many other processes, which implies that synchronization is common or even inevitable (Glass, 2001; Large & Kolen, 1994; Strogatz, 2003). Perhaps human listeners' perception of meter arises from a simple, widespread mechanism of synchronization rather than from unique, music-specific abilities.

3.4. Adult–infant comparisons

Infants can perceive basic aspects of temporal structure in music, but this ability is likely to undergo change with increasing exposure to music. For example, adults' tapping to foreign, unfamiliar music is faster and less flexible than is their tapping to familiar music, which implies that they use culture-specific knowledge to organize temporal information (Drake & El Heni, 2003). The perception of isochrony or equivalence between intervals despite temporal fluctuations (Repp, 1992a) and evidence of cross-cultural differences in tapping to familiar and unfamiliar music (Drake & El Heni, 2003) reveal important influences of implicit knowledge. Such knowledge may require long-term exposure to culturally typical durations, duration ratios, and metrical structures.

There is considerable documentation of biases in the perception and production temporal durations with simple ratios. For example, adults spontaneously produce rhythms with long and short durations in a 2:1 ratio (Fraisse, 1982). Their attempted reproductions of patterns with complex duration ratios reveal stretched or shortened durations to fit simpler ratios (Essens, 1986; Povel, 1981). Even highly skilled musicians simplify duration ratios when they transcribe music (Desain & Honing, 2003). Once listeners interpret a set of durations as a specific simple ratio, that interpretation persists despite otherwise noticeable temporal changes (Large, 2000). These biases are thought to arise from adults' inclination to categorize temporal intervals according to a familiar metrical framework.

Metrical frameworks vary from culture to culture. Although simple duration ratios and isochrony prevail in Western music, music from Eastern Europe, South Asia, Africa, and the Middle East is often characterized by complex duration ratios and non-isochronous metrical structure – designated "complex meter" by some scholars (London, 1995). A prevalent metrical level in much dance music from

Bulgaria and Macedonia consists of non-isochronous, short and long durations that alternate in a 2:3 ratio. When adults of North American, Bulgarian, or Macedonian origin rate the similarity of variations on Bulgarian or Macedonian folk tunes (simple or complex meter), they respond quite differently depending on their cultural background (Hannon & Trehub, 2005a). The ratings of North American adults reflect their culture-specific knowledge of Western metrical structures, with accurate performance in the simple-meter context (i.e., meter-disrupting variations considered less similar to the original than meter-preserving variations), but inaccurate performance in the complex-meter context (i.e., meter-disrupting variations are not distinguished from meter-preserving variations). By contrast, the ratings of Bulgarian and Macedonian reflect their knowledge of both simple and complex metrical structures, with accurate performance in both simple- and complex-meter contexts (Fig. 5). Thus, biases to perceive simple duration ratios in music seem to vary as a function of listening experience.

If biases for categorizing durations on the basis of ratio simplicity depend on culture-specific experience, one would expect differences between infants' and adults' perception of musical rhythm. After 6-month-old infants listen to a folk tune with a simple or complex meter for 2 min, they prefer variations that disrupt the original meter to those that preserve it both for simple and for complex meters (Hannon & Trehub, 2005a). In other words, 6-month-olds' differential responsiveness to meter-preserving and meter-disrupting variations parallels the ratings of Bulgarian and Macedonian adults. By 12 months of age, however, infants respond differentially to meter-preserving and meter-disrupting variations in simple-meter contexts but not in complex-meter contexts (Hannon & Trehub, 2005b). Unlike the culture-general responding of 6-month-olds, 12-month-olds show culture-specific biases like
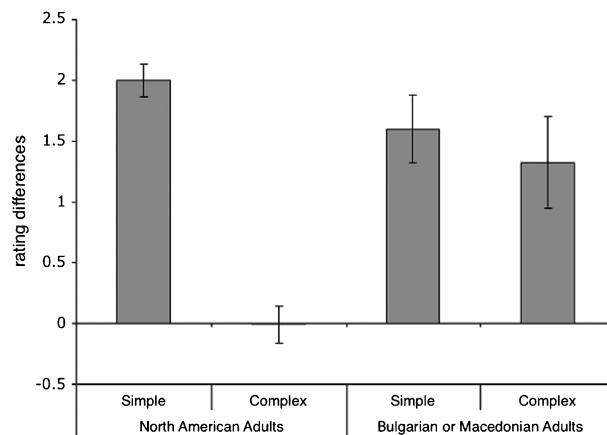

Fig. 5. Rating differences between meter-disrupting and meter-preserving versions for North American and Bulgarian or Macedonian adults (data reformatted with permission from Hannon and Trehub, 2005a, 2005b). Positive differences indicate that meter-disrupting versions are rated as less similar to the original than meter-preserving versions.
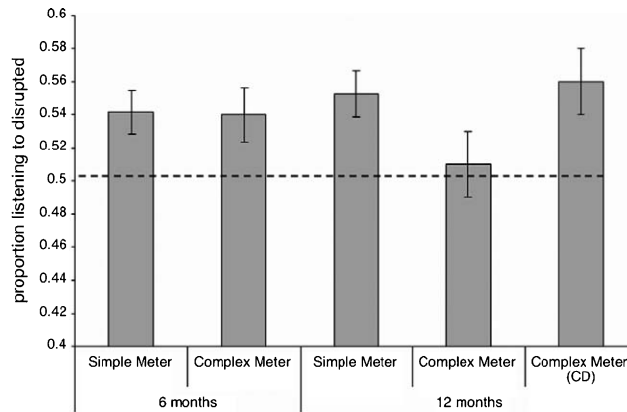
Fig. 6. Proportion of listening time to meter-disrupting versions of simple- and complex-meter tunes (data reformatted with permission from Hannon and Trehub, 2005a, 2005b). Dashed line indicates equivalent listening time to meter-disrupting and meter-preserving versions.

those of North American adults (see Fig. 6). In short, infants' ability to differentiate non-isochronous (foreign) rhythms declines by 12 months of age, which parallels the time frame for declining differentiation of non-native consonant categories (Werker & Tees, 1984).

What is the nature of changing metrical representations, and how do they change? Because the meter-disrupting and meter-preserving variations contained nearly identical alterations (i.e., an added note), it is likely that infants differentiated the variations on the basis of their metrical structure. Perhaps 6-month-old infants are flexible in their perception of complex metrical hierarchies in familiar and foreign music. Alternatively, their implicit knowledge of meter may not be adult-like, even though they can infer some levels of periodic or semi-periodic structure. The latter hypothesis is consistent with developmental and experiential changes in children's and adults' synchronized tapping to music (Drake, Jones, & Baruch, 2000). The implication is that, even after 12 months of age, the perception of rich metrical hierarchies undergoes considerable development. Nevertheless, the early acquisition of adult-like biases in perceiving rhythm and meter contrasts with the protracted developmental course of sensitivity to hierarchical pitch structure (Cuddy & Badertscher, 1987; Trainor & Trehub, 1994).

In the domain of speech perception, infants show remarkable learning on the basis of relatively limited exposure (Kuhl, Tsao, & Liu, 2003; Maye, Werker, & Gerken, 2002). For example, infants readily discriminate foreign speech contrasts at 6 months of age, but they are unable to do so by 10 or 12 months of age (Werker & Tees, 1984) unless they interact with a native speaker of the foreign language for as little as 5 h (distributed over 4 weeks) (Kuhl et al., 2003). Instead of simply registering information passively, the perceptual system may tune representations and knowledge in the course of repeated exposure to particular configurations or distributions of input (Palmeri, Wong, & Gauthier, 2004).

Similar learning mechanisms may underlie developmental changes in infants' perception of duration ratios. After 12-month-olds listen to complex-meter Bulgarian folk tunes for 20 min daily for 2 weeks, they can differentiate meter-disrupting from meter-preserving variations in complex-meter contexts (Hannon & Trehub, 2005b). By contrast, 12-month-olds without such exposure differentiate meter-disrupting from meter-preserving variations only in simple-meter contexts (Fig. 6). North American adults, after 1 or 2 weeks of exposure to complex-meter tunes, remain unable to differentiate meter-disrupting from meter-preserving variations in complex-meter contexts (Hannon & Trehub, 2005b). These findings underscore the importance of early perceptual experience in shaping top-down processing of temporal structures in music. They also imply fundamental differences between infants' and adults' representations. Years of exposure to culture-specific metrical patterns may lead to robust representations that are less amenable to modification than are the weaker representations of novice listeners.

On the basis of the aforementioned findings, we suggest that infants have relatively flexible perception of duration ratios in music, which contrasts with processing biases for small-integer frequency ratios (i.e., consonant intervals) across age (e.g., Schellenberg & Trehub, 1994, 1996a, 1996b), culture (Kilmer et al., 1976), and species (Hulse et al., 1995; Wright et al., 2000). Note, however, that although complex meters are characterized by non-isochronous structure at their most salient metrical level, all other levels in the hierarchy are isochronous. Moreover, the 3:2 ratio of long-to-short durations in complex meters is relatively simple, corresponding to the fundamental frequency ratio of the perfect fifth (seven semitones). Thus, constraints on ratio simplicity may be relevant to temporal as well as pitch structure. When the duration ratio increases beyond 3:2, even highly skilled musicians have difficulty reproducing such rhythms despite extensive practice (Collier & Wright, 1995). Furthermore, the difficulty of bimanual polyrhythmic tapping is predicted by the mathematical complexity of frequency ratios between hands (Treffner & Turvey, 1993).

Constraints on ratio simplicity may apply to behavior across species. For example, the highly structured duets of male and female birds reveal a systematic trajectory from simple to complex ratios (Laje & Mindlin, 2003) that parallels the pattern of spontaneous ratio change in polyrhythmic tapping as a function of increasing speed and difficulty (Peper, Beek, & van Wieringen, 1995). Clearly, much remains to be learned about the significance of ratio complexity in infants' perception of temporal and pitch patterning in music.

4. Conclusion

Infants have a range of pattern processing abilities that enable them to perceive aspects of music in an adult-like manner. Despite adult–infant differences in pitch (Olsho, Koch, & Halpin, 1987) and temporal (Trehub, Schneider, & Henderson, 1995; Werner, Marean, Halpin, Spetner, & Gillenwater, 1992) resolution, there are striking parallels in the perception of pitch relations, consonance and dissonance,

temporal grouping, rhythm, and meter. Peretz and Coltheart (2003) consider these parallels to reflect modular, core mechanisms for human music perception, but the presence of a subset of these skills in non-human listeners raises questions about that perspective. Similarities in the music perception skills of human and non-human listeners are admittedly limited, but the most parsimonious interpretation of the available evidence is that infant skills are a product of general perceptual mechanisms that are neither music- nor species-specific.

This conclusion does not contradict claims about the biological significance of music (Wallin et al., 2000; Zatorre & Peretz, 2001). The universality of music in ritual and caregiving contexts (Dissanayake, 2000; Trehub & Trainor, 1998) lends credence to music, in its broadest sense, as an essential part of the human condition rather than a mysterious, global accident. General-purpose mechanisms may account for the perceptual foundations of music, but special-purpose motivational mechanisms are needed to account for the perpetuation of musical behavior in all human societies. According to Merker (in press), ritual culture requires an innate motivational disposition that may be the most crucial behavioral adaptation of our species. He focuses, in particular, on our motivation to imitate complex but arbitrary forms of vocalization and movement. In the auditory-vocal domain, this ability is shared, to a very limited extent, with whales, seals, and 3 of the 23 orders of birds, all of who learn song patterns from auditory models and invest enormous effort in this endeavor (Janik & Slater, 1997; Merker, in press).

We suggest that universals and adult–infant parallels in music perception reflect biological constraints on information processing, which may operate in concert with species-specific biases and learning constraints (Johnson, 2001). Musical structures may exploit basic properties of perceptual and cognitive systems to meet fundamental social or communicative needs, in line with comparable proposals for language (Bates, Thal, Finlay, & Clancy, 2003; Deacon, 1997; Dunbar, 1996).

Some aspects of the perception of tonality and meter seem to be learned from incidental exposure to culture-specific musical structures. If listeners were unengaged with the music that they hear, they might not acquire the implicit musical knowledge that is shared by most school-aged children and adults. We know, however, that from the early months of life, expressive vocal music promotes contentment (Nakata & Trehub, 2004; Trehub & Trainor, 1998) and modulates arousal (Shenfield, Trehub, & Nakata, 2003). Moreover, infants' attraction to such music seems to be independent of prenatal or postnatal exposure (Masataka, 1999). Nevertheless, infants exhibit rapid learning of socially relevant information, such as their mother's voice (DeCasper & Fifer, 1980), face (Bushnell, Sai, & Mullin, 1989), and odor (Porter, Makin, Davis, & Christensen, 1992). Learning about the music of one's culture may be propelled by comparable social biases, accounting, in part, for infants' more rapid learning of temporal structure than of pitch structure (Hannon & Trehub, 2005b) because of the temporal scaffolding of interpersonal synchrony.

Infants' preference for consonant instrumental music (Trainor & Heinmiller, 1998; Zentner & Kagan, 1996) and tamarins' indifference to music (McDermott, 2005; McDermott & Hauser, 2004) provide a glimpse into the motivational chasm

that separates human from non-human listeners. Because most research on music in human infancy has focused on discrimination, learning, and memory, the contribution of different musical features to early aesthetic preferences is largely unknown. Subsequent listening experience undoubtedly shapes preferences and alters perception to some extent. Ultimately, music processing may become modular or automatized, with modularity being the outcome of development or expertise rather than its impetus, as Karmiloff-Smith (1998) suggests for cognition in general and McMullen and Saffran (2004) suggest for music, in particular.

Acknowledgments

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