11 Musical Development

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I. Origins of Music

Music is a species-specific communication system that develops under a complex set of genetic constraints and environmental input. As with language, some features of musical perception, such as the use of hierarchical pitch and time structures to organize successive sound events, appear to be essentially universal and rest on general capacities and constraints of the human nervous system. And, similar to language, many different musical systems exist, such that through exposure, participation, and/or formal musical training, children become specialized for processing the structure of the musical system(s) in their environment (see Sections III and IV).

During the past couple of decades, research has revealed that the process of becoming specialized for processing the musical structure of one's culture begins early in development and takes many years to complete. Humans are among the most immature animals at birth and have one of the relatively longest periods of development. Although human adults are very similar to other primates in terms of genetic makeup, they have relatively complex brains with large cerebral cortices. This outcome appears to be achieved in large part by an extended period of experience-driven neural plasticity. This extended period of development likely contributes to the unique capacity of humans for generative communication systems, such as music and language, in which novel melodies or utterances are commonly produced. This generative quality also contributes to the cultural changeability of music systems, such that each generation can modify the structural rules of their musical system and incorporate features from foreign musical systems to create new genres.

From an evolutionary perspective, music presents a difficult case, a fact that was recognized even by Darwin (1871), who wrote that music was among the most mysterious faculties of the human species as its adaptive survival value is not clear. Many theoretical perspectives have been proposed since Darwin (e.g., Dissanayake, 2000, 2008; Falk, 2004, 2009; Fitch, 2006; Huron, 2001, 2006; Justus & Hutsler, 2005; McDermott & Hauser, 2005; Miller, 2000; Trainor, 2006; Trehub & Trainor, 1998; Wallin, Merker, & Brown, 2000). According to Pinker (1997), music serves no

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survival value and is simply a useless biproduct of the evolution of language. The problem with this perspective, however, is that it does not explain why music has a long history documented to extend back to Neanderthal culture (Arensburg, Tillier, Vandermeersch, Duday, Scheparts, & Rak, 1989), why it is universal across human societies, or why people past and present expend significant quantities of time and resources on music (Huron, 2001). Darwin himself proposed that music might have evolved for sexual selection, and the idea that musical prowess is an honest signal of health has also been proposed more recently (e.g., Miller, 2000). However, the presence of musical responses early in development (see Section II) suggests that sexual selection is not the whole story. More recently, it has been proposed that music making evolved because it serves a powerful function of cementing social group cohesion (e.g., Hove & Risen, 2009; Kirschner & Tomasello, 2009). Indeed, music is used at virtually all social gatherings, has the power to unite people in emotions from joy to grief, and can incite people to act together, as when fighting an enemy group. An extension of this idea is that music evolved for social-emotional communication between human parents and their infants who, as discussed above, remain immature and helpless for an extended period (Falk, 2009). Indeed, two recent reviews concur that, of all the theories of musical evolution, there is perhaps the most evidence for the idea that musical evolution was driven by advantages incurred by social-emotional bonding, particularly during development (Fitch, 2006; McDermott & Hauser, 2005). Because higher cognitive functions such as music and language depend on experience and learning, it is difficult to determine whether or not these functions are evolutionary adaptations (Trainor, 2006). Furthermore, the evolution of music and language depend on adaptations to a host of nonunique abilities such as working memory capacity and attention. In any case, whether or not musical evolution was specifically driven by survival advantages, we maintain that understanding ontological musical development is crucial for understanding the ultimate origins of music.

In the following sections, we first consider musical development in a social context, examining singing as social communication between infants and caregivers. We also explore what is known about the development of making music with others. We then examine the perception of musical structure very early in development and the acquisition of sensitivity to the particular musical system in the child's environment, with a focus on enculturation to system-specific pitch and rhythmic structures. We also consider how individual emotional responses to music develop and are affected by culture-specific experience. We then examine the development of singing. Before the advent of sound recordings, people needed to create their own music, and typically most members of most societies would participate in singing and/or instrument playing. However, with the wonderful abundance of recordings now readily available on the Internet, it is less incumbent on parents to sing to their children and, indeed, for children themselves to sing. Here we examine the development of singing in relation to the sensorimotor interactions that are necessary for its execution. In Western culture, there is a wide range of musical training experienced, from virtually none to extensive formal music lesson experience beginning at an early age. We review the effects of these different experiences on the acquisition of musical expertise and also on relations between music and other cognitive domains such as language, spatial-temporal processing, memory, attention, and general intelligence. Finally, we summarize what is known about musical development, outline the major as-yet unanswered questions, and consider what musical development can tell us about the importance of music in human evolution.

II. Musical Development in a Social Context

A. Singing to Infants

Infants' first postnatal experiences of music most commonly occur in the context of social interactions with their caregivers. Not only is music a cross-cultural universal, but singing to infants is ubiquitous as well (e.g., Falk, 2009; Papousek, 1996; Trehub, 2001; Trehub & Trainor, 1998). Descriptions of the use of music with infants and young children date back to the ancient Greek philosophers and have been described for many cultures, including regions in India, Africa, Europe, and Eastern Asia (see Custodero, 2006; Ilari, 2005; Trehub & Trainor, 1998). Even in Western North American society, where recorded music abounds, analyses of diary reports indicate that the majority of mothers sing to their infants at many times throughout the day during activities such as playing, bathing, feeding, diaper changing, car travel, and going to sleep (Trehub, Unyk, Kamenetsky, et al., 1997). In this section, we explore what important functions infant-directed (ID) singing serves that have sustained it as a universal care-giving activity. We will examine the features of ID singing as well as what infants attend to and extract from ID singing. Although children do not themselves produce songs until sometime later in development, as discussed in Section IV, these initial interactive experiences in infancy set the stage for musical learning.

If singing to infants evolved to serve particular functions, songs for infants would be expected to have similar characteristics across different cultures. Although there is very little empirical work on this question, the available evidence suggests that lullabies, which by definition have the intended function of soothing infants and encouraging them to sleep, have perceptually identifiable features across cultures and musical systems. Trehub, Unyk, and Trainor (1993a) examined ethnomusicological recordings from diverse cultures, including South America, Europe, and the Middle East, and extracted tracks of songs identified as lullabies. For each lullaby they chose a song from the same recording that was not intended for an infant but was matched in tempo. Western adults were above chance levels at choosing which of each pair was the lullaby despite their lack of familiarity with the musical systems in question. They were still also able to do this task when the recordings were low-pass filtered at 500 Hz, which eliminated access to word and phonetic information, an important control condition as lullabies might contain more nonsense syllables, repeated syllables, and onomatopoeia than songs for adults. Further study showed that adults rated the lullabies as having more simple structure and that adults were more likely to classify songs as lullabies when they had few changes in pitch direction and a preponderance of falling pitch contours (Unyk, Trehub, Trainor, & Schellenberg, 1992). Interestingly, a study using instrumental versions of songs from collections of native North American music suggests that Western adults can distinguish lullabies from all other song categories except love songs (see Trehub & Trainor, 1998). This result suggests that lullabies might, in part, reflect the love of parents for their infants.

Studies of singing to infants in present North American culture suggest that there are two main categories of songs for infants, lullabies and play songs (Trainor, 2006; Trehub & Trainor, 1998), with lullabies intended for calming, soothing, and inducing sleep, and play songs intended for arousing, playing, and engaging infants in social interaction. Although particular songs may be associated with one of these two categories of ID singing—for example, "Hush Little Baby" and "Rock-a-bye Baby" are lullabies whereas "Itsy Bitsy Spider," "Skinamarinki-dinki-dink," and "The Wheels on the Bus" are play songs—much of the distinction lies in *how* a song is sung rather than the *structure* of the song itself. Indeed, many songs such as "Twinkle, Twinkle Little Star" are used for both purposes, and many parents sing popular adult songs, adapting them for their infant audience. It is possible that there are cross-cultural differences in the relative use of lullabies and play songs. Trehub, Unyk, and Trainor (1993b) recorded English-speaking and Hindi-speaking mothers singing a song of their choice to their infant. They found that English-speaking mothers sang arousing play songs most often, while Hindi-speaking mothers sang soothing lullabies most often.

Although songs tend to be classified by adults as lullabies or play songs according to their words, the words probably make little difference to preverbal infants. Indeed there is evidence that across cultures mothers sometimes sing soothing lullabies with words that are far from soothing: for example, in English, "when the bough breaks the cradle will fall, down will come baby, cradle and all." Trehub proposed that the words may be in some cases cathartic for the mother and describes making a recording of a mother in Turkey singing a tranquil song to her infant, only to discover later after having the words translated that the mother was expressing discontent toward the baby's absent father (Trehub & Trainor, 1998). Trainor and colleagues (Rock, Trainor, & Addison, 1999; Trainor, 1996) proposed that the distinction between lullabies and play songs is less in the words sung or even the structure of the music, but largely in the *performance characteristics* or the *manner* in which the caregiver produces the song. Rock et al. (1999) recorded mothers singing a song of their choice to their infant. Half of the mothers were asked to sing a song to put their infant to sleep and half to sing a song to play with their infant. Subsequently each mother was asked to sing the same song in the opposite manner. The sample contained mostly songs in English, but there were songs in French, German, and Hebrew as well. The lullaby and play song versions of the same song sung by each mother were paired and played to adult raters. Adults were 100% accurate at determining which of each pair was the play song and which the lullaby rendition. Independent groups of adults subsequently chose the play song of each pair as rendered in a more smiling tone of voice, as more brilliant, and as more rhythmic. They chose the lullaby as sounding more airy and more soothing. Furthermore, play songs were chosen as sounding more clipped and containing more pronounced consonants whereas lullabies were chosen as sounding smoother. Thus, play song and lullaby styles can be established on the basis of performance characteristics. Additionally, infants were videotaped while listening to the lullaby and play song renditions. When adults viewed clips without sound from these recordings, they were able to tell above chance levels when infants were listening to plays songs and when to lullabies. Thus the two styles of singing have different effects on infants' behavior. In particular, infants tended to focus attention outward to the external world during play songs, but more inward toward themselves during lullabies.

Two main functions of infant-directed singing have been proposed (Trainor, 2006; Trainor, Clark, Huntley, & Adams, 1997). One concerns emotional communication and the regulation of the infant's state. Music in general not only conveys information about musical emotion but directly induces emotion in human listeners (e.g., Huron, 2006; Juslin & Sloboda, 2001; Meyer, 1956; Salimpoor, Benovoy, Longo, Cooperstock, & Zatorre, 2009). Adults can experience shivers down the spine, laughter, tears, lump in the throat, changes in heart rate and breathing rate, and sweating responses when listening to music (e.g., Krumhansl, 1997; Nyklicek, Thayer & Van Doornen, 1997; Sloboda, 1991; Trainor & Schmidt, 2003). Children are also sensitive to emotional meaning in music (Cunningham & Sterling, 1988; Trainor & Trehub, 1992b). Human infants, perhaps in part because they are born in a relatively immature state, are not good at regulating their emotional state, and it is the role of caregivers to calm infants when they are upset and to rouse infants in order to direct their attention to interesting people and things in the environment. Acoustic analyses have confirmed the distinction between lullabies and play songs and suggest that particular performance characteristics of ID singing help caregivers to achieve different caretaking goals associated with emotional communication and state regulation. Trainor et al. (1997) measured various acoustic features, comparing ID and non-ID performances of lullabies and play songs. They found that ID versions of both lullabies and play songs were rendered at a higher pitch than non-ID versions, consistent with other studies of ID singing (Bergeson & Trehub, 1999; Trehub, Unyk, et al., 1997). Higher pitch is likely related to emotional expression. Across many species, lower-pitched vocalizations are associated with aggression whereas higher vocalizations are associated with appeasement, submission, and friendliness (Morton, 1977), and such associations may relate to the fact that larger objects tend to produce lower sounds. Increased pitch is also associated with the expression of joy in speech (Scherer, 1986). The timbre or quality of the voice carries additional information about emotion. With increased emotion, there is less control over vocal cord movement, leading to increased jitter (frequency variation at the smallest time period) and shimmer (amplitude variation at the smallest time period) and pitch variation within vowels (e.g., Bachorowski & Owren, 1995). Trainor et al. (1997) found increased jitter for both ID lullabies and play songs and increased shimmer and pitch variability for ID play songs, suggesting that emotion is heightened for ID singing in general, and likely more so in the case of play songs than lullabies. Interestingly, smiling also affects voice quality as it changes the shape of the vocal tract, and the expression of pleasant emotions can cause faucial and muscle pharyngeal changes that result in relatively more energy at low frequencies than at high frequencies (e.g., Tartter, 1980; Tartter & Braun, 1994). Relatively more energy at low than high frequencies was found for ID versions of both lullabies and play songs, again suggesting that ID singing involves the expression of positive emotions.

The second function of ID singing suggested by Trainor et al. (1997) concerns helping infants process auditory patterns by exaggerating structural features such as phrase boundaries, rhythm, and grouping. Acoustic analyses suggest that caregivers use ID play songs to a greater extent than ID lullabies for this function (Trainor et al., 1997). Both ID play songs and ID lullabies contained longer pauses between phrases compared with non-ID versions, thus clearly delineating this aspect of the song structure. Songs in both ID styles were rendered more slowly in the presence of the infant, consistent with Trehub, Unyk, et al. (1997). However, length of phrase-final syllables plus following pauses (i.e., onset of phrase-final syllable to onset of the next phrase) and relative duration of stressed to unstressed syllables were only greater for ID compared with non-ID versions of play songs. Thus, caregivers appear to exaggerate acoustic features delineating musical pattern structure to a greater extent in play songs than in lullabies, although they do so to some extent in both cases. Processing temporal organization is critical for perceptual and cognitive development in general and for learning musical and language structure in particular (see Longhi, 2009, for a review). Temporal coordination between infants and caregivers is important for successful development of social interactions and regulation of emotion (e.g., Lewkowicz, 1989, 2000). Recent evidence suggests that mothers actually delineate the hierarchical beat structure when they sing to infants using both acoustic accents and movements (Longhi, 2009). Interestingly, mothers appear to emphasize upbeats the most, perhaps because the upbeats provide anticipatory information that a strong downbeat will follow. Indeed, it has been proposed that meaning in music arises through the process of creating expectations and experiencing whether or how they are fulfilled (Huron, 2006; Meyer, 1956). Infants in Longhi's study showed some understanding that all beats are not the same, making more synchronous movements to the beginning and end beats of each phrase.

It is interesting that engaging in ID singing appears to be an intuitive response elicited during interaction with an infant and is, in fact, just one behavior in a repertoire of interactive behaviors that parents engage in, which include rocking, smiling, laughing, talking, and playful touching (e.g., see Trehub, Unyk, et al., 1997). Several studies indicate that when recordings of mothers singing a song to their infant are compared with recordings of the same mother singing the same song in the absence of her infant, adult raters can distinguish the ID and non-ID versions (Trainor, 1996; Trehub et al., 1993b). Furthermore, even when instructed to sing in the same way that they would sing to their infant (simulated ID singing), adult raters can still distinguish the real ID versions, suggesting that the presence of the infant is necessary for full elicitation of the ID singing style (Trehub, Unyk, et al., 1997). Importantly, depressed mothers have been found to sing faster and with less emotional expression than nondepressed mothers (de l'Etoile & Leider, 2011), which may have significant detrimental effects on the attachment and social-emotional development of their infants.

Fathers and other siblings also engage in ID singing, but to a lesser extent than mothers. Trehub, Unyk, et al. (1997) found that in a diary study of singing to infants over the course of a day, mothers produced 74% of all ID songs, fathers 14%, siblings 8% and other people 4%. Despite the fact that fathers sing much less to their infants, adult raters can discriminate ID from simulated ID versions of fathers' singing (Trehub, Unyk, et al., 1997), and they rate ID versions as more rhythmic, loving, and appropriate for infants compared with non-ID versions (O'Neill, Trainor, & Trehub, 2001). Furthermore, fathers make similar modifications as mothers when singing to their infants, raising the pitch and slowing the tempo of their songs (Trehub, Unyk, et al., 1997). Interestingly, there is some suggestion that fathers sing more expressively to their male infants than to their female infants, whereas mothers sing more expressively to their female infants than to their male infants (Trehub, Hill, & Kamenetsky, 1997), again consistent with the idea that singing is intimately involved in social interaction.

Analyzing the vocalizations of caregivers is important for understanding the nature and functions of ID singing, but it is also crucial to understand the effects of such singing on infants. Trainor (1996) recorded mothers singing a song of their choice in two versions, one directed to their infant and the other sung in the absence of their infant. Adults were very accurate at distinguishing ID from non-ID versions and were also consistent in whether they rated an ID sample as a lullaby or a play song. Trainor then tested infants' preferences for the two versions in a preferential looking paradigm in which trials presenting the ID and non-ID versions alternated, and the infant controlled how long they listened on each trial by their looking behavior—each trial continued as long as the infant looked at a light and toy display and ended when the infant looked away. She found that infants preferred (looked longer in order to hear) the ID versions to the non-ID versions. Thus, infants show preferences to listen to maternal ID over non-ID singing. One study indicates that infants also prefer to listen to fathers' ID over non-ID singing, but only when the ID versions were higher in pitch than the non-ID versions (O'Neill et al., 2001), so more research is needed in order to understand infants' responses to fathers' singing. Certain characteristics of ID singing appear to be particularly important for infant preferences. Tsang and Conrad (2010) found that infants preferred to listen to higher-pitched renditions of play songs, as did Trainor and Zacharias (1998), but to lower-pitched renditions of lullabies, consistent with the idea that infants understand the emotional messages of these singing styles. In a further study Conrad, Walsh, Allen, and Tsang (2011) found that infants preferred faster tempos for play songs but not for lullabies, again consistent with their differentiation of these styles. The importance of positive emotion for infants is also evident in their preference for a loving tone of voice. Trainor (1996) found that the degree to which infants preferred ID over non-ID versions of songs was correlated with adult ratings of how much more loving the ID version was compared with the non-ID version. Importantly, infants' salivary cortisol levels change after exposure to maternal singing (Shenfield, Trehub, & Nakata, 2003).

It is difficult to examine infants' responses to singing compared with other positive caregiving behaviors because it is difficult to match stimuli across conditions. However, it appears that infants react as positively to ID singing as they do to being read a story or engaged in play with a toy (de l'Etoile, 2006). Nakata and Trehub (2004) report that 6-month-olds look longer in order to see audiovisual episodes of their mother engaging in ID singing compared with ID speech. It is unclear, however, whether this reflects a general preference for music over speech, something about the ID singing style, engagement in the rhythmicity of the singing, or the relative novelty of the singing, as mothers may engage in more speech than singing when interacting with their infants. In any case, regardless of comparisons to other infant-directed behaviors, it is clear that infants react positively to ID singing, that they react differently to lullaby and play song styles of singing, and that these responses can be seen in both behavior and physiological measures.

Caregivers not only sing to preverbal infants, but they talk to them as well, and much work has been done on the characteristics of ID speech. In general, across cultures ID speech is, compared with adult-directed speech, higher in pitch, slower in tempo, more rhythmically regular, more repetitive, and more exaggerated in prosodic pitch contour (Ferguson, 1964; Fernald, 1989; Grieser & Kuhl, 1988; Papousek, Papousek, & Symmes, 1991). Thus, it could be argued that ID speech and singing are more similar than are non-ID speech and singing. In speech, as in music, structural features such as phrase boundaries and metrical structure are exaggerated (e.g., Bernstein Ratner, 1986; Fernald & Kuhl, 1987; Fernald & Mazzie, 1991; Jusczyk et al., 1992), suggesting that ID speech, like ID singing, helps infants to process auditory temporal patterns. However, at least in early infancy, the main function of ID speech may be to communicate emotional information and regulate an infant's state. Many studies show that infants attend to ID speech and prefer ID speech to adult-directed speech (e.g., Fernald, 1985; Werker & McLeod, 1989). Infants' positive emotional response to ID speech suggests that it is important for social and emotional development. Infants pay particular attention to the musical features of ID speech, such as its exaggerated pitch contours, leading some to refer to ID speech as musical speech (Fernald, 1989). Young infants gaze longer at silent faces of individuals who previously used ID speech than to individuals who previously used adult-directed speech, suggesting that ID speech can enhance infants' social preferences for caregivers who use it (Schachner & Hannon, 2011). Moreover, the pitch contours appear to convey emotional meaning. Soothing utterances are delivered with a relatively small pitch range and falling pitch contours, whereas attention-getting utterances use large bell-shaped pitch contours (Fernald, 1989, 1991; Fernald & Simon, 1984; Papousek et al., 1991; Sachs, 1977; Stern, Spieker, Barnett, & MacKain, 1983; Stern, Spieker & MacKain, 1982). Not all ID speech is positive, however, as mothers also use ID speech to warn infants of danger. Infants' understanding of prosodic emotional meaning is evident in their preference for approving over disapproving ID utterances

(Fernald, 1992, 1993). The central role of emotional expression in ID speech has led to the idea that ID speech is not really a special register for infants; rather ID speech has the acoustic features that it does because caregivers typically express emotion to infants. Indeed Trainor, Austin, and Desjardins (2000) found that ID and adult-directed expressions of love-comfort, fear and surprise are actually acoustically similar. What is different is that adults are typically emotionally expressive with infants whereas they are much less so with other adults.

The preceding paragraph suggests that ID speech and singing contain some similar acoustic features and serve similar functions. Another characteristic that they share is that both appear to be elicited intuitively. Simulated ID speech (Fernald & Simon, 1984; Jacobson, Boersma, Fields, & Olson, 1983) and music (Trehub, Unyk, et al., 1997) are not the same as when caregivers are actually interacting with infants. Furthermore, mothers adjust their ID speech depending on the infants' reaction. In a controlled study, Smith and Trainor (2008) had mothers watch their infant, who was located in the next room, on a video screen and vocalize to him or her through a microphone. They were instructed to try to keep their infant happy through their talking. In fact, the infant could not hear the mother's voice. Out of view of the camera on the infant, one of the experimenters either smiled and interacted with the infant or ignored the infant. For half of the mothers, the positive interaction occurred whenever the mother raised the pitched of her voice and for the other half of mothers, the positive interaction occurred when the mother lowered the pitch of her voice. Thus the infant's positive reaction served as positive reinforcement for the mother to either raise or lower the pitch of her voice. Mothers whose babies displayed a positive reaction when she raised the pitch of her voice spoke in a higher pitch than mothers whose babies displayed a more neutral or negative reaction. A similar controlled study has not been done with ID singing, but it would be expected that mothers would make similar intuitive adjustments. It remains an open question as to whether music or language evolved first, or whether a proto music-language existed from which both music and language evolved. What does appear to be the case is that in development, music and language begin rather undifferentiated and become differentiated with increasing age and experience.

In sum, ID singing appears to exaggerate structural elements in music, paving the way for infants to learn the structure of the music in their environment. As will be discussed in Section III, over a period of years, children become enculturated to the structure of the music system of their culture without any formal musical training. However, the effect of ID singing on this process remains largely unknown. Apart from acquainting infants with the structure of music in their culture, ID singing appears to serve the important functions of emotional communication between caregiver and infant and of helping infants to regulate their states. Indeed Falk (2009) has proposed that music and then language evolved with the need to tend to a human infant born in a very premature state and with a long developmental trajectory to reach maturity. In conjunction with the idea that music serves the function of social bonding regardless of age, a plausible argument can be made that music is an evolutionary adaptation. It will be interesting to see whether, with the unprecedented access to recorded music available today, singing interactions between parents and infants will become less frequent, or whether the social-emotional functions they serve are so strong that they will remain largely unaffected.

B. Entrainment and Making Music Together

It has often been noted that music is used across cultures at virtually all rituals and important social gatherings, from weddings, funerals, and religious ceremonies to parties, sporting events, and political rallies, suggesting that engaging in musical behavior in synchrony with others leads to social cohesion and cooperation within social groups (e.g., Bispham, 2006; Brown & Volgsten, 2006; Fitch, 2006; Huron, 2001; McNeill, 1995; Merker, 2000). A few studies in adults support this idea. Participating in a group singing lesson was found to lead to more cooperation in a game of prisoner's dilemma and higher reported trust levels compared with participating in group poetry reading or passively watching a film or listening to music together (Anshel & Kipper, 1988). And more cooperation was found in group games after synchronous versus asynchronous singing, achieved by having people sing along to songs played over headphones that were in synch or out-of-synch with each other (Wiltermuth & Heath, 2009). Furthermore, when people were instructed to tap in time to their own auditory or visual signal, those whose signals were set up so that they tapped in synchrony with each other reported liking their partners more than those whose signals were set up so that they tapped asynchronously (Hove & Risen, 2009). Social effects of synchrony have been found with children as young as 4 years of age, who participated in a pretend-play game that did or did not involve singing and walking together in time to the song, but was otherwise the same (Kirschner & Tomasello, 2010). After this experience, children who had sung together showed more cooperation during games involving collective problem solving and more spontaneous helping behavior during a game (helping the other child when his or her marbles fell due to a faulty container).

The necessary conditions for increased social cohesion in music making are not entirely clear, but entraining to a common beat may be one of the most powerful aspects in this regard. Many aspects of movement are rhythmical, including locomotion, heartbeats, and vocalizations, and many species engage in rhythmic movements, including movements that are synchronized across individuals as when birds fly in a flock and fireflies pulsate together. However, entraining movement to the tempo of an external auditory beat is relatively rare across species and is likely limited to those that are capable of vocal learning (Patel, Iversen, Bregman, & Schulz, 2009; Schachner, Brady, Pepperberg, & Hauser, 2009). In humans, this ability is likely established through oscillatory brain networks (Fujioka, Trainor, Large, & Ross, 2009) encompassing auditory and motor areas of the brain (Fujioka, Trainor, Large, & Ross, 2012). Functional magnetic resonance imaging (fMRI) studies indicate that listening to a rhythm is enough to activate motor regions (Grahn & Rowe, 2009; Zatorre, Chen, & Penhune, 2007) and that an auditory beat will modulate activity in the beta band (15–30 Hz) that follows the tempo of the beat in both auditory and motor areas (Fujioka, Trainor, Large, & Ross, 2012).

Developmentally, young infants can discriminate different beat tempos (Baruch & Drake, 1997) and different auditory rhythm patterns (see Section III,B), but they do not appear to be able to entrain their movements to a beat (Longhi, 2009; Zentner & Eerola, 2010). It is not clear whether this reflects a lack of connection between auditory and motor systems or the immaturity of movement control, but some research suggests the latter. Phillips-Silver and Trainor (2005) found that infants bounced on either every second beat or on every third beat of an ambiguous rhythm (i.e., with no accents) later preferred to listen to a version of that rhythm with accents that matched how they were bounced, indicating that when moved by another person, infants do exhibit auditory-motor rhythmic interactions.

Before 4 years of age, there is little evidence that children are able to entrain to a beat. It has been reported that 3-year-olds have great difficulty clapping to a metronome beat (Fitzpatrick, Schmidt, & Lockman, 1996) and that the tapping of 2.5-year-olds appears to be synchronized only when the tempo of the beat is around a 400-ms interstimulus interval (ISI), which is close to their spontaneous tapping rate (Provasi & Bobin-Bègue, 2003). Similarly, the whole body movements of children younger than 4 years (hopping, swaying, circling) do not generally follow the tempo of the music to which they are listening (Eerola, Luck, & Toiviainen, 2006). However, by 4 years, there is ample evidence for entrainment (Drake, Jones, & Baruch, 2000; Eerola et al., 2006; Fitzpatrick, et al., 1996; McAuley, Jones, Holub, Johnston & Miller, 2006; Provasi & Bobin-Bègue, 2003). From a social perspective, it is interesting that when drumming with an adult social partner, children as young as 2.5 years will adjust their tempo toward that of their partner (Kirschner & Tomasello, 2009). In a well-controlled study, these authors compared the accuracy of children's entrainment with an adult drumming (listening to the beat over headphones so as not to be swayed by the child's rhythmic productions) to their entrainment with a nonhuman machine that hit a drum, and with an auditory-only rhythm. They found that all children between 2.5 and 4.5 years were more accurate when drumming with a social partner and that the 2.5-year-olds only showed entrainment when drumming with the human social partner. The social nature of such effects are also revealed in a study showing that children synchronize more accurately with an adult partner than they do with a child partner (Kleinspehn-Ammerlahn et al., 2011).

Entrainment is one aspect of a larger set of behaviors known as joint action, where two or more individuals coordinate their actions (see review by Knoblich, Butterfill & Sebanz, 2011). Such coordination is important for human social interaction, being essential for activities from language conversations to accomplishing physical goals such as lifting something too heavy for one individual. Entrainment often occurs at a preconscious level, as when pedestrians match their walking patterns (Van Ulzen, Lamoth, Daffertshofer, Semin & Beek, 2008), people in conversation synchronize their body sway (Shockley, Santana, & Fowler, 2003), and audience members synchronize their clapping (Neda, Ravasz, Brechte, Vicsek, & Barabasi, 2000). Entrainment between adults in tapping tasks has been well studied (for reviews see Knoblich et al., 2011; Repp, 2005). Although infants likely lack the motor coordination to engage in entrainment, the roots of joint action from which entrainment likely emerges can be seen very early in development. When interacting with infants, caregivers provide temporally structured input across a number of modalities including speech, music, facial expression, and touching (Koester, Papousek, & Papousek, 1989; Stern, Beebe, Jaffe, & Bennett, 1977). For example, Stern et al. (1977) found that 64% of maternal phrases uttered were repeated in a temporally regular pattern. Because entrainment requires the ability to predict when the next event is likely to occur, such stimulation could provide scaffolding for the development of entrainment. Furthermore, there is evidence that caregivers are sensitive to the social behaviors of infants in their interactions. Brazelton, Koslowski, and Main (1974) observed that infants have internal timing cycles for arousal and attention that lead to alternations between engagement in the interaction and withdrawal, as evidenced by turning away or pushing away or sleeping, fussing, or crying. Mothers are sensitive to these cycles and modify their behaviors accordingly, which appears to help infants process information and regulate their state (e.g., Papousek & Papousek, 1981). Amount of coordination between mothers and infants at 3 and 9 months predicts self-regulation, IQ in childhood, and empathy in adolescence (see Feldman, 2007 for a review). Perhaps most convincingly, Longhi, 2009 analyzed mothers' singing to their infants and measured when infant behaviors (head, body, hand, and leg movements) were synchronized with the beat of the music. Interestingly, infants synchronized their behaviors the most to the beats at the beginning, midpoint, and end of the phrases, showing the beginnings of entrainment behavior.

In sum, rhythmic interaction is present between infants and caregivers from a very early age, and there is evidence that it is important for bonding between them as well as for future social development. Although young infants do not appear to have the motor capability to coordinate their actions with a musical rhythm, their perception of rhythm is influenced by movement. By the preschool years, children can coordinate their actions with an external beat, and entraining with others leads to group cohesion and increased prosocial behavior.

C. Conclusions

Across cultures, infants are exposed to music from the beginning in a social context as caregivers sing to them. Furthermore, caregivers modify their singing in order to accomplish caretaking goals such as regulating their infant's state. Before infants are able to motorically entrain to an auditory rhythm, they experience concurrent auditory and movement rhythms as their caregivers rock and bounce them while singing. By the preschool years, joint music making and joint rhythmic entrainment are evident and are associated with prosocial behavior. Although the evolutionary origins of music remain controversial, this research lends strength to the idea that music evolved to promote social bonds and group cooperation, which was particularly necessary in order for parents to protect and invest in infants who remained immature for a long period of time.

III. Musical Enculturation and Critical Periods for Musical Acquisition

Just as there are many different languages, there are many different musical systems. And just as a child exposed to a particular language will learn that language without formal instruction, a child exposed to a particular musical system will develop brain circuits specialized for processing the spectral and temporal structure of that musical system (Hannon & Trainor, 2007; Trainor, 2005; Trainor & Corrigall, 2010; Trainor & Unrau, 2012; Trehub, 2003a, 2003b, 2005). In order to understand this process of enculturation, it is necessary to examine the developmental trajectories for acquisition of sensitivity to different structural features of the musical system in question. Musical structure can be thought to encompass two basic interacting domains, spectral structure (including pitch, scales, tonality, and harmony) and temporal structure (including metrical and grouping structure). These will be considered in turn, in the following sections. Unfortunately, almost all research on musical enculturation concerns Western tonal music, so the discussion will largely be limited to this system. The extent to which the general principles outlined here apply across musical systems remains for the most part an important topic for future research.

A guiding principle of enculturation is that musical structures that are more universal are acquired earlier than those that are more rare across cultures. This principle is consistent with the idea that universal features are more likely to reflect the capabilities and constraints of sound processing in the auditory system, including characteristics of the ear, the nature of circuits in the brain stem and the ease of forming particular representations at cortical levels. According to this idea, less universal musical structures would be more likely to reflect structures that are more difficult to learn and thus be acquired at a later developmental stage.

A. Spectral Processing

In this section, the development of sensitivity to musical pitch features will be considered. Musical pitch has a hierarchical structure (Krumhansl, 1990; Shepard, 1964). Individual tones are composed of harmonics that are integrated into the percept of a single sound with pitch. Tones stand in particular relations to each other, such that tones with similar fundamental frequencies sound similar, but also that tones separated by an octave sound similar. Furthermore, tones are combined sequentially into melodies and simultaneously into chords. Acquisition of sensitivity to these different aspects of pitch structure are considered in this section, beginning with features that are relatively universal and acquired early and progressing to features that are more system-specific and acquired later. The discussion will focus largely on the *perception* of music. The development of singing *production* will be considered in Section IV.

Determining what infants and young children perceive is not always straightforward, and it is expedient to obtain converging evidence by using different methods. Behaviorally, infant discrimination can be tested by rewarding infants for increasing the frequency of a specific, spontaneously occurring behavior. With young infants, for example, the strength and number of sucks that they make can be changed when they are rewarded with their mother's voice. Alternatively, infants can be rewarded for looking at one object when presented with one sound or sound category and at another object when presented with another sound category. When infants reach about 5 months of age, they have the motor control to turn their heads and can be rewarded with animated toys for turning toward a loudspeaker when there is a change in an ongoing train of stimuli in what is known as a conditioned head-turn paradigm.

Early sensitivity can also be measured by using event-related potentials (ERPs; the brain's response to an event such as a sound presentation) derived from the electroencephalogram (EEG) recorded at the surface of the head (e.g., see Luck, 2005; Trainor, 2012). For example, the synchronous depolarization of many neurons whose axons are oriented in the same direction between cortical layers in auditory areas around the Sylvian fissure creates an electrical field that can be measured at the surface of the head, with a negativity at frontal sites and a positivity at occipital sites (or vice versa). The stages of sound-event processing can be tracked through the series of positive and negative peaks in the ERP. Subcortical processing is seen in the first 15 ms after sound onset in the auditory brain stem responses. In adults, middle latency responses from primary auditory cortex occur between about 15 and 40 ms, and responses from secondary auditory cortex and beyond occur after that (e.g., N1, P2, N2, P3, where N and P indicate frontal negativity or positivity, respectively, and the number indicates the temporal order of the components). As will be discussed later, cortical responses in young infants are very immature, are dominated by slow waves not seen in adults (Trainor, 2008, 2012), and don't reach adult levels until well into the teenage years (Ponton, Eggermont, Kwong, & Don, 2000; Shahin, Roberts, & Trainor, 2004).

One other component of interest is the mismatch negativity (MMN), which represents the brain's preattentive monitoring of an unexpected event. MMN is typically elicited in an oddball paradigm in which one sound in an ongoing repetition of a sound (or exemplars from a sound category) is occasionally replaced by a sound differing in a feature (e.g., pitch, duration, loudness, timbre, location) or violating an expected pattern such as an upward pitch contour (Näätänen, Paavilainen, Rinne, & Alho, 2007; Picton, Alain, Otten, Ritter, & Achim, 2000; Trainor & Zatorre, 2009). In adults, it manifests as a frontally negative, occipitally positive component peaking between 130 and 250 ms after onset of the oddball stimulus. Mismatch responses are present in the newborn period, although they manifest initially as frontally-positive slow waves. Thus mismatch responses are very useful for measuring auditory discrimination during infancy.

1. *Early Developing Pitch Abilities*

a. Integrating Harmonics into a Percept of Pitch

Sounds that give rise to a sensation of pitch (as opposed to noises) typically have energy at a fundamental frequency and a series of harmonics with energy at integer multiples of that frequency. When presented with a complex tone, the inner ear performs a sort of Fourier analysis, with different frequencies maximally displacing the basilar membrane at different points along its length. Different hair cells of the auditory nerve along the length of the basilar member are thus maximally activated for different frequencies, leading to a tonotopic map organization that is maintained through subcortical pathways and into primary auditory cortex. When two or more overlapping sound sources are present, the sound waves they emit (and their reflections off surfaces in the environment) sum and reach the ear as one complex wave. The auditory system must figure out which components belong to which sound source, a process termed auditory scene analysis (Bregman, 1990). One heuristic used by the auditory system is to group together harmonics whose frequencies are all integer multiples of a common fundamental frequency because they likely all originated from the same sound source, and doing so gives rise to the sensation of pitch. Thus, the sensation of pitch is not given in the stimulus; rather, it is derived through the integration of related frequency components and likely evolved as a consequence of auditory scene analysis. Interestingly, although sound frequency information is clearly processed subcortically, pitch is likely first derived in a region adjacent to primary auditory cortex (Fishman, Reser, Arezzo, & Steinschneider, 1998; Patterson, Uppenkamp, Johnsrude, & Griffiths, 2002; Penagos, Melcher, & Oxenham, 2004; Schönwiesner & Zatorre, 2008; see Chapter 1 and Chapter 6, this volume, for detailed discussions).

The perception of the pitch of isolated tones is a prerequisite for musical perception in most contexts, and such processing is likely similar across different musical systems. Infants discriminate frequency differences from before birth (e.g., Lecanuet, Granier-Deferre, & Busnel, 1988; Shahidullah & Hepper, 1994), although adult levels of discrimination are likely not reached until 8 to 10 years of age (Werner & Marean, 1996). However, by 2 months of age, frequency discrimination is certainly within the limits needed for perception of musical structure (Werner & Marean, 1996; He, Hotson, & Trainor, 2009).

Because pitch perception appears to rely on auditory cortex, the early immaturity of auditory cortex might predict that pitch perception is not functioning at birth. A common method of measuring pitch perception that ensures that the task is not being accomplished by processing the frequencies of individual harmonics is to employ complex tones with the fundamental frequency removed. Removal of the fundamental does not alter the pitch, although it does change the timbre. However, in order to perceive the pitch of the missing fundamental, the harmonics must be integrated into a pitch percept. Behaviorally, Clarkson and colleagues used the conditioned head-turn method to demonstrate that 7-month-old infants perceive the pitch of the missing fundamental (Clarkson & Clifton, 1985). He and Trainor (2009) tested younger infants using ERPs. They presented standard trials consisting of tone pairs, where each tone contained a fundamental frequency and some harmonics but each tone contained different harmonics. For each tone pair, the fundamental frequency and the frequency of every harmonic rose from the first to the second tone. On the occasional deviant (oddball) trials, every frequency component also rose from the first to the second tone, but the components of the second tone were chosen so that they created a missing fundamental that was lower than the fundamental frequency of the first tone. Thus, if a listener were only following frequency components, they would all rise from the first to the second tone as in the standard tone pairs. However, if the listener were following the pitch, it would rise on the standard trials but fall on the deviant trials, and a mismatch response would be expected. Clear mismatch responses were found at 4 months of age, but no hint of mismatch response was found at 3 months of age, suggesting that true pitch perception emerges between 3 and 4 months of age.

In sum, the frequency discrimination needed for music perception is in place before birth and basic pitch perception by 4 months of age. Basic pitch perception is likely a consequence of general auditory scene analysis, which is seen across many species and is critical to parsing auditory input into the sound objects present in the environment. In this light, it makes sense that basic pitch perception emerges early and is employed similarly across musical systems.

b. Sensory Consonance and Dissonance

When two tones are presented simultaneously in the absence of a context of other tones, adults consistently rate them on a scale from consonant (pleasant) to dissonant (unpleasant or rough) (e.g., Kameoka & Kuriyagawa, 1969; Levelt, van de Geer, & Plomp, 1966). This phenomenon is referred to as sensory consonance. The consonance/dissonance continuum is also used in musical composition and is one of the features that contributes to the ebb and flow of tension (dissonance) and its resolution (consonance) that gives rise to musical meaning (Smith & Cuddy, 2003) and is thus an important musical device. Tones whose fundamental frequencies stand in simple integer ratios tend to be heard as consonant, such as the octave (2:1) and perfect fifth (3:2). In such cases, many of the harmonics are identical in frequency, and those that are not tend to be more than a critical bandwidth apart (about ¼ octave for most of the frequency range). On the other hand, tones whose fundamentals stand in more complex integer ratios tend to be heard as dissonant, such as the major seventh (15:8) and the tritone (45:32). In these cases, there are many nonidentical harmonics across the two tones that are less than a critical bandwidth apart. The most prominent theory of consonance proposes that dissonance arises at the level of the basilar membrane in the inner ear (Plomp & Levelt, 1965). Frequencies that are less than a critical bandwidth apart cause vibration patterns on the basilar member that cannot be separated, and their interaction gives rise to the sensation of beating and/or roughness. A competing theory is that consonant and dissonant intervals set up distinct temporal firing patterns in the auditory nerve (Tramo, Cariani, Delgutte, & Braida, 2001). Recent evidence in favor of the latter theory is a study in which adults ratings of consonance and dissonance were found to be related to the harmonicity between two tones (i.e., how close their harmonics come to integer multiples of a common fundamental) but not to roughness (McDermott, Lehr, & Oxenham, 2010).

Regardless of which theory is correct, both indicate a relatively peripheral origin for sensory distinctions between consonance and dissonance, suggesting that sensitivity to this feature should arise early in development. Several studies indicate that this is the case. Infants show asymmetric detection, more readily detecting a semitone change to a consonant interval that results in a dissonant interval than detecting a whole tone change to a dissonant interval that results in a consonant interval (Schellenberg & Trainor, 1996). Infants are also better at detecting an occasional dissonant interval embedded into a series of consonant intervals than the reverse (Trainor, 1997). The effects also appear to generalize from the simultaneous presentation of tones to the sequential presentation. Infants are better at detecting changes in melodies composed of consonant intervals than changes in melodies composed of dissonant intervals (Trainor & Trehub, 1993). Infants also appear to have an intrinsic preference for consonance, as infants as young as 2 months of age prefer to listen to consonant intervals rather than dissonant intervals in isolated and musical contexts (Trainor & Heinmiller, 1998; Trainor, Tsang, & Cheung, 2002; Zentner & Kagan, 1998). Even hearing newborn infants of deaf parents show this preference (Masataka, 2006).

An early preference for consonance is somewhat difficult to explain, but it might be related to the fact that because the harmonics of two dissonant tones interfere on the basilar membrane and in the auditory nerve firing patterns, the identity of two simultaneous dissonant tones is more difficult to discern than the identity of two consonant tones. On the other hand, highly consonant intervals such as octaves have so many harmonics in common that the two notes comprising them tend to blend into one tone. In any case, the perceived similarity of tones an octave apart is also very common across musical systems (Burns, 1999). In Western musical theory, tones an octave apart are given the same note name and when people sing together who have different voice ranges, they will sing in octave intervals. Given its likely peripheral origin, it is not surprising that infants are also sensitive to octave relationships (Demany & Armand, 1984).

We cannot underestimate the importance of octave equivalence and the consonance/dissonance continuum for musical structure as these two factors have a large influence on the construction of the musical scales from which music is composed. The fact that sensitivity to both emerges early in development suggests that they are fundamental building blocks of musical pitch structures.

c. Relative Pitch

One fundamental aspect of music is that tunes and motifs retain their identity regardless of what pitch they start on. The ability to recognize melodies in transposition relies on a relative pitch encoding that is based on the intervals between notes rather than on their absolute pitch level. Despite the fact that tonotopic maps are pervasive in the ascending auditory pathway, memory for absolute pitch tends to fade quickly, and the ability to name notes in isolation is quite rare (Bachem, 1955; Brown et al., 2003). Although absolute pitch is sometimes considered to be a gift, relative pitch involves more complex processing and is likely the more useful ability for music. Interestingly, relative pitch is found early in development. Infants are able to detect deviances in short repeating melodies even when the melodies are transposed from trial to trial, and they tend to treat two repetitions of a melody at different pitch levels as the same (Chang & Trehub, 1977a; Trainor & Trehub, 1992a; Trehub, Bull, & Thorpe, 1984). Furthermore, for both infants and adults, determining whether two tones have the same or a different pitch becomes more difficult the more interference tones that are placed between them (e.g., Plantinga & Trainor, 2008; Ross, Olson, Marks, & Gore, 2004). There is also evidence that infants encode melodies in long-term memory in terms of relative pitch. Plantinga and Trainor (2005) exposed infants at home to one of two short melodies every day for a week. Subsequently, in the lab, infants were exposed to trials of the two melodies and controlled how long they listened to each melody, as the trial began when infants looked towards a visual display and ended when they looked away from the display. Infants preferred to listen to the novel melody over the melody to which they had been exposed. Furthermore, when another group of infants was tested on their preferences for two versions of the melody heard at home, one at the pitch level heard at home and one transposed, they showed no preference for either version. These results suggest that relative pitch is salient to young infants but that absolute pitch is not. ERP data also indicate that 6-month-old infants show mismatch responses to occasional changes in a four-note melody repeating in transposition, again indicating relative pitch processing (Tew, Fujioka, He, & Trainor, 2009).

Most of the studies just described involved infants 6 months of age and older, so how young infants encode pitch remains unknown. It has been proposed that there is an absolute-to-relative developmental shift in pitch processing, where young infants have an initial bias toward absolute properties of pitch that is gradually replaced by the more useful strategy of relative pitch processing (Takeuchi & Hulse, 1993). Consistent with this proposal, absolute pitch is more common among individuals who begin music training during early childhood (Takeuchi & Hulse, 1993) or among those who speak a tone language (Deutsch, Henthorn, Marvin, & Xu, 2006). One statistical learning study reported that infants learned pitch patterns on the basis of absolute but not relative pitch relations, whereas adults learned on the basis of relative but not absolute cues (Saffran & Griepentrog, 2001). However, this study stands out as an exception given the abundant evidence for relative pitch processing in infants, reviewed earlier. Moreover, some sensitivity to absolute pitch information is evident in listeners of all ages (Levitin, 1994; Schellenberg & Trehub, 2003, 2008; Volkova, Trehub, & Schellenberg, 2006), which casts further doubt on the notion that listeners lose sensitivity to absolute pitch information as they mature. Perhaps listeners of all ages are sensitive to both absolute and relative pitch information, but relative pitch plays an increasingly important role in listeners' conceptions of musical patterns. This possibility is supported by a study that asked 5- to 12-year-old children and adults to rate the similarity of melodic pairs when one melody was an exact repetition of the other, a transposition, a same-key melodic variation (with altered interval and contour structure), or was a transposed melodic variation (Stalinski & Schellenberg, 2010). They reported a gradual developmental shift where younger children found absolute pitch changes (i.e., transpositions) more salient than melodic changes, whereas older children found melodic changes more salient than transpositions. This result suggests that relative pitch information may play an increasingly prominent role in children's conceptions of melody up until age 12, presumably as a result of prolonged exposure to music that emphasizes relative pitch (via frequent transpositions) over absolute pitch. (See Chapter 5, this volume, for a detailed discussion of absolute pitch.)

In sum, the ability to integrate harmonics into a percept of pitch, the perception of consonance and dissonance, and the ability to encode relative pitch all develop early. These aspects of pitch are likely experienced similarly across cultures and play an important role in most musical systems.

2. Later Developing Pitch Abilities: Enculturation to Western Tonality

Because musical intervals and harmonic syntax differ from musical system to musical system, these aspects of musical structure must necessarily be learned. Even Western adults without formal musical training who, for example, cannot name musical notes and who do not have explicit knowledge of scale or harmonic structure, have considerable implicit knowledge of Western tonality as revealed in both behavioral and ERP studies (e.g., Bigand & Poulin-Charronnat, 2006; Bischoff Renninger, Wilson, & Donchin, 2006; Koelsch, Gunter, Schröger, & Friederici, 2003; Koelsch, Schmidt, & Kansok, 2002; Krumhansl, 1990; Tillmann, Bigand, Escoffier, & Lalitte, 2006; Trainor & Trehub, 1994). This sensitivity has presumably been acquired through incidental everyday exposure to Western music.

There are some commonalities across musical systems. Most musical systems use scales that divide the octave into between five and nine intervals. The use of a small number of discrete pitches is presumably related to memory limitations and parallels the use of a small number of phonemes in languages. Some aspects of musical scale structure are relatively universal, such as octave equivalence, the use of prominent consonant intervals, and the use of two or more interval sizes that enable different notes of the scale to relate differently to the other notes and thereby take on different functions (Balzano, 1980). Interestingly, infants show better processing of unfamiliar scales containing two interval sizes rather than one (Trehub, Schellenberg, & Kamenetsky, 1999).

Different musical scales divide the octave differently, so key membership, that is, knowing which notes belong in a key and which do not, must be learned. Young infants can encode and remember short melodies by as young as 2 months of age (Plantinga & Trainor, 2009). And as young as 6 months (the youngest age tested), infants can remember melodies for weeks (Ilari & Polka, 2006; Saffran, Loman, & Robertson, 2000; Trainor, Wu, & Tsang, 2004). However, young infants appear insensitive to key membership. At 8 months of age, Western infants can equally well detect changes in a Western melody that either stay within the key or go outside the key of that melody, whereas musically untrained Western adults are much better at detecting the out-of-key than within-key changes (Trainor & Trehub, 1992a).

Furthermore, in one of the only cross-cultural studies in this domain, Lynch, Eilers, Oller, and Urbano (1990) showed that although musically untrained Western adults are much better at detecting changes in melodic patterns based on the Western major scale compared with an unfamiliar Balanese scale, infants perform equally well in both cases. Several studies suggest that knowledge of key membership is in place by at least as young as 4 years of age. Four- and 5-year-old children can better detect a change in a tonal than in an atonal melody (Trehub, Cohen, Thorpe, & Morrongiello, 1986) and are like adults in performing better at detecting changes in a melody that go outside the key compared with changes that remain within the key (Corrigall & Trainor, 2010; Trainor & Trehub, 1994). Finally, one study suggests that a general sensitivity to tonality can emerge by 1 year of age if infants participate in music classes for infants and their parents (Gerry, Unrau, & Trainor, 2012; Trainor, Marie, Gerry, Whiskin, & Unrau, 2012).

Sensitivity to harmony appears later in development (e.g., Costa-Giomi, 2003), in line with the relative rarity of complex harmonic syntax across musical systems. Trainor and Trehub (1994) found that 7-year-old, but not 5-year-old, children performed better at detecting changed notes in a Western melody that violated the implied harmony compared with changed notes that were consistent with the implied harmony, even though both types of changes remained within the key of the melody. Using a probe-tone technique in which a key context is given and then notes are rated for how well they fit the context, Krumhansl and Keil (1982) found that it was not until 8 years of age that children showed differential responses to different within-key notes, indicating sensitivity to implied harmony, although Cuddy and Badertscher (1987) and Speer and Meeks (1985) demonstrated some sensitivity by 6 years of age with a simplified task. Examining processing of chord sequences as opposed to implied harmony in melodies, Schellenberg and colleagues (Schellenberg, Bigand, Poulin-Charronnat, Garnier, & Stevens, 2005) used an implicit task in which children judged whether the timbre of the final chord in a sequence was a piano or a trumpet. They found faster responses when the final chord conformed to the rules of Western harmony than when it did not. Similarly, using ERPs, Koelsch and colleagues (Koelsch, Grossman, et al, 2003; Jentschke, Koelsch, Sallat, & Friederici, 2008) found that 5-year-old children showed differential brain responses to large harmonic violations but not to more subtle violations to which adults were sensitive. Finally, when in the context of a familiar melody, even 4-year-olds will choose accompanying chord sequences that are harmonically appropriate over those that are not, although it is not clear the extent to which this response is based on familiarity or harmonic knowledge (Corrigall & Trainor, 2010).

These studies indicate that the beginnings of enculturation to the tonal system in a child's environment can begin as early as 1 year of age and that implicit knowledge of key membership is in place by at least as young as 4 years of age. The beginnings of sensitivity to harmonic syntax can be seen at 5 years of age, but probably do not reach the level of musically untrained adults until several years later. This progression follows the relatively common use of musical scales with discrete pitches across musical systems (although the particular scales vary from system to system) and the relatively rare use of complex harmony.

B. Temporal Processing

With its rich and dynamic structure, music requires listeners to segment events into meaningful groups, remember and reproduce patterns of temporal duration, form expectations for future events, and move in synchrony to a beat. Perception of grouping, rhythm, beat, and meter are thus essential components of musical competence (see Chapter 9, this volume). Recent evidence suggests that listeners are strikingly sensitive to musical temporal structure from an early age. At 4 to 6 months of age, infants already exhibit sensitivity to grouping boundaries in music, as shown by their differential responsiveness to subtle temporal changes that fall within but not between grouping boundaries established by pitch patterning (Thorpe & Trehub, 1989), duration (Trainor & Adams, 2000), or a combination of pitch and duration (Jusczyk & Krumhansl, 1993). Infants as young as 2 months of age can discriminate simple rhythmic patterns that have contrasting successive patterns of duration (such as 100-600-300 ms versus 600-300-100 ms) (Chang & Trehub, 1977b; Demany, McKenzie, & Vurpillot, 1977; Lewkowicz, 2003), and they do this even in the presence of concurrent changes to the pitch level and tempo of rhythms (Trehub & Thorpe, 1989).

As described earlier (Section II,B), synchronous movement to music, such as dancing, is universal and may have important social functions, but the capacity to move in precise synchrony with a beat is limited in the youngest listeners. Nevertheless, perceptual sensitivity to periodicities in music may emerge very early in development. For example, at 7 months of age, infants who are habituated to simple rhythmic sequences that conform to either duple or triple meters exhibit a subsequent novelty preference when presented with rhythms that violate the previously established meter, even when component intervals and temporal grouping structures are matched across rhythms (Hannon & Johnson, 2005). When newborns are presented with drum patterns containing occasional omissions, they exhibit larger mismatch-negativity ERPs to omissions occurring on the downbeat than omissions occurring on upbeats, suggesting that newborns differentially process events occurring at strong versus weak metrical positions (Winkler, Haden, Ladinig, Sziller, & Honing, 2009). These results suggest that human listeners may be able to infer an underlying pulse with minimal prior experience or learning.

Even if young infants can infer a beat from periodically regular patterns, they may nevertheless acquire hierarchical metrical representations or categories that influence beat induction in a top-down fashion (Desain & Honing, 2003). Just like harmony and scale structure, metrical structures can vary from culture to culture, and therefore cross-cultural and developmental comparisons provide a window onto the effects of culture-specific listening experience on rhythm and beat perception. Western music typically contains isochronous beats, with different beat levels in the metrical hierarchy multiplying or subdividing adjacent levels by two or three (Lerdahl & Jackendoff, 1983). Because of the tendency for rhythms to conform to isochronous meters, rhythms in Western music tend to be composed of durations that stand in simple 2:1 or 1:1 ratios, which may explain why Western listeners have difficulty perceiving, remembering, reproducing, and tapping synchronously to rhythmic patterns containing more complex duration ratios (Essens, 1986; Essens & Povel, 1985; Fraisse, 1982; Hannon & Trehub, 2005a; Repp, London, & Keller, 2005; Snyder, Hannon, Large, & Christiansen, 2006). By contrast, music from various regions of the world (the Balkans, South Asia, Africa, and South America) contains beat levels that are not isochronous, with the primary beat level containing alternating long and short durations in a 3:2 ratio (London, 2004). Accordingly, individuals from Turkey and India, who are accustomed to nonisochronous meters, do not exhibit enhanced perception and production of 2:1 than 3:2 ratios (Hannon & Trehub, 2005a; Hannon, Soley, & Ullal, 2012; Ullal, Hannon & Snyder, under revision).

Growing evidence suggests that biases toward culture-specific metrical structures are probably acquired some time during the first year after birth. North American adults have difficulty noticing beat-disrupting changes to a melody with a nonisochronous meter even though the same type of change is readily detected in the context of an isochronous meter (Hannon & Trehub, 2005a; Hannon et al., 2012). By contrast, 4- to 6-month-old North American infants perform comparably whether the stimulus has an isochronous or nonisochronous meter (Hannon & Trehub, 2005a; Hannon et al., 2011), an ability that declines between 7 and 12 months of age (Hannon & Trehub, 2005b; Hannon, Soley, & Levine, 2011). These developmental changes appear to be experience driven, as shown by the finding that at-home listening to CDs containing nonisochronous meter music can reverse developmental declines among 12-month-olds and young children but not among adults or older children over the age of 10 (Hannon & Trehub, 2005b; Hannon, der Nederlanden, & Tichko, in press). Listening experiences may even influence metrical processing within a given culture, as shown by the finding that American 9-month-olds are better at detecting disruptions to a duple-meter than a triple-meter melody, presumably because triple meter is less prevalent than duple meter in Western music (Bergeson & Trehub, 2006). This trend even appears to be accelerated among 7-month-old infants who are exposed to more duple- than triple-meter music in Kindermusik classes (Gerry, Faux, & Trainor, 2010; see also Section V,C).

Enhanced processing of culturally familiar meters may arise after infants begin to exhibit listening preferences for the meter of their own culture. When presented with songs having a simple, isochronous meter and songs having a complex, nonisochronous meter (typical in Balkan music), American infants prefer listening to the isochronous-meter song, a preference that increases in strength from 4 to 8 months of age (Soley & Hannon, 2010). By contrast, when presented with the same pairs of songs, Turkish infants exhibit no listening preferences, even though they exhibit preferences for songs having isochronous or nonisochronous meters when paired with songs having highly complex, highly irregular meter atypical in any culture (Soley & Hannon, 2010). These results raise the intriguing possibility that listening preferences precede and perhaps give rise to processing advantages for familiar meters.

Experience appears to play a crucial role in shaping developing metrical processing among young listeners, but it presumably operates in tandem with auditory system constraints. For example, although metrical ratios of 3:2 pose no initial difficulty for young infants, even 4-month-old infants who do not yet exhibit own-culture biases nevertheless have difficulty detecting disruptions when rhythms contain more complex ratios such as 7:4 (Hannon et al., 2011). Similarly, 6-month-olds are better at detecting rhythm and pitch deviants to a melody whose rhythm has been deemed "good" by adult listeners than a melody whose rhythm has been deemed "bad" (Trehub & Hannon, 2009). Infants prefer listening to the more regular of two rhythms, even when neither is familiar (Nakata & Mitani, 2005; Soley & Hannon, 2010), a bias that may reflect the intrinsic aversiveness of temporally unpredictable sequences to human and nonhuman listeners alike (Herry et al., 2007). Thus, universal constraints on temporal processing, reflected in biases present in early infancy, might limit the types of metrical structures that are present in any given culture.

To summarize, the perceptual foundations of rhythm, beat, and meter are evident in listeners as young as a few days of age. Young listeners can *perceive* musically meaningful temporal structures before they can actually *produce* or synchronize their movements with music. Although early listening experience shapes some aspects of temporal processing (e.g., rhythm and meter perception), other aspects, such as rhythm discrimination and beat induction, may occur spontaneously and require little experience.

C. Development of Emotional Responses to Music

As hinted at earlier, aesthetic responses to music are evident very early in development and may reflect universal ways in which emotion can be conveyed through music. As reviewed above, infants universally prefer infant-directed vocalizations to other types of vocalizations, and they respond appropriately to different emotional messages contained in infant-directed speech (Section II,A). Likewise, within days of birth infants exhibit preferences for consonant pitch combinations (Section III,A,1) and for temporally regular or predictable patterns (Section III,B). These findings are consistent with cross-cultural evidence suggesting that certain acoustic features of music universally evoke emotional responses or interpretations. For example, North American and Japanese listeners use the same acoustic features (tempo, loudness, and complexity) to label the emotions conveyed in passages of unfamiliar (Hindustani) instrumental music (Balkwill & Thompson, 1999; Balkwill, Thompson, & Matsunaga, 2004).

On the other hand, given the demonstrated importance of listening experiences in shaping culture-specific musical knowledge, it should come as no surprise that the ability to label and categorize musical emotions develops throughout childhood and depends on increasingly diverse cues. When children are presented with computerized melodies (Gerardi & Gerken, 1995; Kastner & Crowder, 1990), sung melodies intended to convey contrasting emotions (Adachi, Trehub, & Abe, 2004; Dolgin & Adelson, 1990) or pieces of music rated by adults as highly expressive and representative of certain emotions (Cunningham & Sterling, 1988; Esposito & Serio, 2007; Giomo, 1993; Kratus, 1993; Nawrot, 2003), children as young as 4 years of age have been shown to accurately label musical emotions such as happiness and sadness, although accuracy improves with age. When tempo, loudness, mode, and other potential cues to musical emotion are varied systematically, it becomes clear that 3- to 4-year-old children primarily rely on tempo and loudness, whereas it is not until 6 to 8 years of age that children use mode (major/minor) as a cue to musical emotion (Dalla Bella, Peretz, Rousseau, & Gosselin, 2001; Gerardi & Gerken, 1995; Gregory, Worrall, & Sarge, 1996). When 4- to 12-year-old children are asked to express specific target emotions in their performances of songs, their "happy" renditions are faster, louder, and at a higher pitch level than their "sad" renditions (Adachi & Trehub, 1998). These cues are sufficient for same-age peers from other cultures to accurately decode the intended emotion of each performance, even when the listener cannot understand the words (Adachi et al., 2004). When lyrics conflict with musical cues to emotion (such as mode, tempo, and other expressive cues), 5- to 10-year-old children tend to focus on the semantic content of the lyrics (e.g., "I lost all my money on the way to the store") and ignore the expressive cues in the sung performance, while adults do the opposite (Morton & Trehub, 2007). When lyrics are absent, children and adults both use the same acoustic cues to determine the emotion of the singer (Morton & Trehub, 2007).

In summary, although infants and children are sensitive to some affective information in music such as emotion conveyed through tempo, pitch level, and loudness, they must also acquire some basic knowledge of key and harmony in order to interpret other cues, such as mode.

D. Conclusions

Just as there are many different languages in the world, there are many different music systems. Through exposure, children become sensitive to the structures in the musical system of their culture, and they lose sensitivity to structures not found in their native musical system. At the same time, sensitivity to features that are common across musical systems appear very early, such as discrimination of consonance and dissonance, the ability to encode relative pitch, and beat induction. Culture-specific features such as particular musical scales, harmonic structure, and particular metrical structures are acquired later according to the general principle that more common features are acquired earlier than rare features. A similar progression can be seen for affective information in music, such that children understand the meanings of universal features such as tempo, pitch level and loudness before they understand the meanings of culture-specific features such as mode.

IV. Music Production: Development of Singing

Singing is probably the most universal form of musical production with a deep evolutionary origin. Singing is used for many purposes, including the transmission of knowledge, the easing of everyday pressures, and mate selection in courtship

(Brown, Martinez, Hodges, Fox, & Parsons, 2004; Huron, 2001; Tsang, Friendly, & Trainor, 2011). Perhaps most importantly, singing together can promote social cohesion and prosocial behavior and can give a sense of identity among those singing the same music (Booth, 1981; Kirschner & Tomasello, 2010). Despite the important social role that singing can play, relatively little research has been done on singing development. The greater research emphasis on perception over production of music might result from the difficulty of studying singing behavior.

Singing, like language, emerges spontaneously without formal instruction (Dalla Bella, Giguere, & Peretz, 2007) and singing accuracy increases with age. In one of the few comprehensive frameworks for singing development, Welch (2006) outlined 7 stages of development, from early childhood (1–3 years) through to senescence. In terms of particular singing behaviors, Welch (1986) proposed that singing behaviors develop in a fixed order. His observations suggest that young children focus more on the words than the pitches of a song, producing a chant-like effect. Gradually, children incorporate general pitch contours and make up song fragments. Pitch intervals gradually become more accurate. Initially pitch may wander from phrase to phrase, but eventually pitch errors become rare, at least for simple familiar songs. The small amount of existent literature is generally consistent with this trajectory, although much more data is needed.

Because singing necessarily involves an interaction between both motor and auditory modalities, it would be expected to lag behind perceptual development, which presumably depends only on development of the auditory modality. Furthermore, because most singing involves words, it necessarily involves interactions between music and language. As these two systems compete for the resources necessary for production, this interaction also could lead to delays in production compared with perception. In the following sections, we focus on the early origins of production during infancy, the development of pitch accuracy and singing in key, and the role of experience in the development of good singing.

A. From Cooing to Song

Even in adult productions, the boundary between speech and singing is not always clear. For example, when a phrase of speech is repeated over and over, the perception of the listener is that it suddenly changes from speech to song (Deutsch, Henthorn, & Lapidis, 2011). That the same acoustic signal could be perceived as either speech or song suggests that this classification likely depends on a number of factors including perception, cognition, context, and interpretation of the intentions of the speaker or singer. Given that infant-directed speech is highly repetitive and has exaggerated pitch contours, it is perhaps not surprising that it sometimes appears to be sung. Interestingly, the early vocalizations of infants, although classified as precursors of speech by linguists, could equally be classified as precursors of singing (see Adachi, 2011). The early cooing and babbling of infants is typically repetitive and contains glissandi (pitch glides) that are most often downward in direction (Jerslid & Bienstock, 1931; Michel, 1973; Moog, 1976; Reis, 1987, Welch, 1994). These pitch glides can cover a wide pitch range (195–1035 Hz,

G_3−C_6; Fox, 1990; Moog, 1976). According to Dowling (1984), it is not until children are 2 years of age that their speech and singing are reliably distinct. With respect to learning a new song, young children appear to focus first on the words, with accurate rhythm and pitch coming later. Children also invent new songs, and by at least as young as 5 years of age, these songs contain distinct phrases that are typically two or four bars long (Davies, 1992).

Speech and song are produced by the same physiological systems, including the lungs, throat, larynx, tongue, and oral and nasal cavities, and so they presumably recruit similar motor regions of the brain. There is also evidence that processing speech and music recruits similar parts of the brain (Koelsch et al., 2002) and, indeed, that rhythmic characteristics of a language affect the musical compositions of its speakers (see Section VI,C). In terms of voice quality, there is a correlation between the speaking and singing voices of 10-year-old children as rated by trained adults (Rinta & Welch, 2009), suggesting commonalities between the production of speech and singing. In general, with increasing age, vocal quality improves (Hanna, 1999; Leighton & Lamont, 2006), children are able to sing louder, and relatively more energy is concentrated at harmonics below 5.75 kHz (Sergeant & Welch, 2008).

With increasing age, the average pitch of the speaking voice decreases, but the range of the singing voice increases. Between 7 and 10 years of age, the singing range increases by about half an octave, from an average of G_3 to C_5 (196−524 Hz) at age 7 to an average of F_3 to $E\flat_5$ (175−622 Hz) by age 10 (Welch et al., 2010). Vocal range appears to be highly variable and to depend on singing experience. Some 4-year-olds have a range similar to the range of adults, and practice increases pitch range by about 30% (Jerslid & Beinstock, 1931).

Over the course of development, there are also changes in the amount of singing children engage in. In situations where singing is expected, the amount of time children spend singing generally increases between kindergarten and third grade (Hornbach & Taggart, 2005; Rutkowski & Snell Miller, 2003; Welch et al., 2008), although this effect appears to depend on a number of factors and is not always found consistently (Levinowitz et al., 1998; Mang, 2006). One interesting finding is that children exclusively learning a tone language appear to acquire use of the singing voice earlier, again suggesting an interaction between the development of speech and musical production (Mang, 2006).

B. Pitch Accuracy and Singing in Key

The most common measure of singing proficiency is pitch matching, whether of individual tones, glides, or melodies. The majority of people develop good pitch matching abilities even without formal musical training (Bentley, 1969), although there is a wide range of abilities in the normal adult population (Amir, Amir, & Kishon-Rabin, 2003; Pfordresher & Brown, 2007). In general, children's ability to pitch match improves with age (e.g., Cooper, 1995; Davies & Roberts, 1975; Flowers & Dunne-Sousa, 1990; Geringer, 1983; Green, 1994; Howard & Angus, 1997; Mang, 2006; Petzold, 1966; Trollinger, 2003; Welch, Sergeant & White, 1996, 1997, 1998; Yarbrough, Green, Benson, & Bowers, 1991).

Experience also plays a significant role in the development of good singing. Chinese-speaking children show better singing performance than English-speaking children in first grade, perhaps because learning a tonal language trains pitch perception and production (Rutkowski & Chen-Haftek, 2000). Different kinds of formal instruction also appear to have different effects. In particular, vocal instruction involving visual and kinesthetic aspects appears to lead to better pitch accuracy compared with simple group singing in kindergarten children (Apfelstadt, 1984). In one study, 5- to 6-year-old children were more accurate at singing melodies if they had learned them accompanied by gestures than if they had learned them without gestures (Liao, 2008), particularly if the songs contained difficult leaps or high notes (Liao & Davidson, 2007). Of course, it is possible that the use of kinesthetics and gesture simply makes singing more fun and that children therefore are better able to attend, but in any case, these studies indicate that instruction method is important for achieving optimal singing development.

The ability to sing a melody accurately depends on more than vocally matching the pitch of isolated tones. As discussed in the preceding section, through everyday exposure to music, children become enculturated to the pitch structures of the musical system in their environment. There is evidence that this perceptual reorganization helps children to sing melodies with pitch structures that conform to the rules of their musical system (Flowers & Dunne-Sousa, 1990; Mang, 2006). The ability to maintain a tonal center through a song was found to improve between 3 and 5 years of age as defined by modulations of less than a quarter tone (Flowers & Dunne-Sousa, 1990). Similarly, using trained raters, Mizener (1993) found that children in fourth and fifth grades were better able to maintain a key than were children in third grade.

Good singing almost certainly depends on general cognitive factors such as memory. Given that memory continues to improve well into the school age years (e.g., Case, Kurland, & Goldberg, 1982; Gathercole, Pickering, Ambridge, & Wearing, 2004; Siegel, 1994), this may account for some of the improvement with age. Indeed, even in adults, reducing the cognitive load by decreasing linguistic demands results in more accurate singing (Berkowska & Dalla Bella, 2009b). However, the findings in children are equivocal. Some studies indicated that singing in children is more accurate without lyrics (e.g., see Welch, 2006; Yarbrough et al., 1991), others that singing is more accurate with lyrics (Hanna, 1999) and still others that there is no difference (Levinowitz et al., 1998; Sims, Moore, & Kuhn, 1982). Interestingly, boys appear to be more disadvantaged by the lyrics than are girls (Welch, 2000), consistent with generally better verbal skills in girls than boys early in development. One factor that might contribute to these discrepancies is that when learning a song, children will tend to focus first on the words and later on the pitch (Levinowitz et al., 1998; Welch, Sergeant, & White, 1998). It is possible that whether the lyrics hinder or enhance singing accuracy depends on how overlearned the song is.

In sum, singing accuracy improves with age but is also affected by a number of other factors such as whether musical instruction includes multisensory experience, familiarity, and cognitive and memory demands.

C. Learning to Sing as a Sensorimotor Task

Learning to sing well involves a complex interplay between auditory and motor systems (see also Chapter 3, this volume). The singer must first retrieve pitch and timing information from memory, then map this information onto motor plans in order to produce the desired sounds, and finally perceptually monitor this output in order to make fine adjustments to the motor plan (Berkowska & Dalla Bella, 2009a). The role of perception is evident from a number of studies in adults. For example, singing accuracy is improved when supported by a perceptual signal from the external environment, as when singers sing along with an accurate singer or group of singers (Pfordresher & Brown, 2007; Wise & Sloboda, 2008). Several studies report a positive correlation between pitch matching accuracy and perception of melodies (Demorest, 2001; Demorest & Clements, 2007; Phillips & Aichison, 1997), again suggesting that good perceptual abilities aid singing production. If altered perceptual feedback about one's singing is delivered online using headphones, singing accuracy suffers (e.g., Jones & Keough, 2008; Pfordresher & Varco, 2010; Zarate & Zatorre, 2008). One way to conceptualize the role of perception when singing is as an "internalized" or imagined voice. This idea is supported by evidence that adults' pitch matching is best when the model is in the timbre of one's own voice than when it is another person's voice or a complex tone (Moore, Estis, Gordon-Hickey, & Watts, 2008).

It is possible that poor singing in adults could be caused by problems at the perceptual stage, the motor planning stage, or the interaction between perception and motor planning. Although about 15% of the adult population self-label as "tone deaf," likely about 5% actually have a perceptual deficit (Sloboda, Wise, & Peretz, 2006). The term "tone deaf" is also sometimes used to describe individuals who cannot sing accurately. However, perception and production problems do not always go hand in hand, as some poor singers can perceive pitch accurately but cannot reproduce it accurately (e.g., Dalla Bella et al., 2007; Loui, Guenther, Mathys, & Schlaug, 2008; Pfordresher & Brown, 2007). The deficit in such individuals is presumably at either the motor planning stage or the interaction between perception and motor planning. It is also the case that individuals who are perceptually tone deaf still sometimes produce accurate pitch to some extent, for example, producing the correct up-down direction for intervals they cannot perceive (Loui et al., 2008; Pfordresher & Brown, 2007).

Developmentally, it is not known what limits young children's singing accuracy and what drives improvements with age (Tsang et al., 2011). Basic motor skills are in place early on, as infants are able to babble, but considerable refinement of laryngeal control, lung and rib capacity, and so on takes place over many years (Trollinger, 2003). Motor programs for song production presumably also become more refined with increasing age. Auditory perception is reasonably sophisticated early on, such that young infants can combine harmonics into the perception of complex tones (He & Trainor, 2009), discriminate complex tones that are a quarter tone apart (Trainor, Lee, & Bosnyak, 2011) and discriminate melodic and rhythmic patterns, but again, improvements are seen for many years (see Trainor &

Corrigall, 2010; Trainor & Unrau, 2012; Trehub, 2010, for reviews). There are few studies examining the correlation in young children between pitch matching and pitch perception abilities (for a discussion see Tsang et al., 2011) making it difficult to determine whether integration between perception and motor planning might be one factor limiting good singing early in development. A few studies suggest that children are better able to imitate a voice model that is similar to their own voice, whether a female voice (having a more similar range to children than a male voice) or a child voice (Green, 1990; Petzold, 1969; Yarbrough et al., 1991) although not all studies find this difference (Small & McCachern, 1983). Finally, as discussed earlier, there is evidence that the amount and kind of experience and instruction in singing affects the development of accurate singing in children. It remains for future research to determine how auditory perception and motor production interact through development to enable good singing.

D. Conclusions

The origins of speech and singing can be seen in infancy with the repetition and pitch modulation of infants' babbling. With increasing age, children's singing and speaking voices become more differentiated. The development of accurate pitch in singing takes many years to develop, but most adults can sing simple familiar songs with good accuracy. The developmental time course of singing accuracy can be greatly affected by amount and type of singing experience. Although it is clear that good singing depends on accurate auditory perception, refined motor planning, and an exquisite interaction between these two systems, there is little research on the developmental trajectories of these separate factors and how they affect the development of singing. Given the important social functions of singing and the potential decrease in singing behavior in modern society, the development of singing in children is an important area for future research.

V. Effects of Formal Music Training on Musical Development

A. Differences between Adult Musicians and Nonmusicians

Musicians usually begin taking formal music lessons during childhood, and they spend significant amounts of their time engaged in concentrated practice and intensive music listening. Given this enriched early musical experience, an intriguing question is whether or not such experiences change and improve the development of musical skills and abilities. In recent decades, this question has been examined in numerous studies comparing how adult musicians and nonmusicians perceive and produce musically relevant structures. Relative to nonmusicians, trained musicians exhibit superior pure and complex tone discrimination (Tervaniemi, Just, Koelsch, Widmann, & Schroger, 2005), greater sensitivity to changes in melodies (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004, 2005), faster pitch processing speed (Micheyl, Delhommeau, Perrot, & Oxenham, 2006; Schellenberg & Moreno, 2010; Strait, Kraus, Parbery-Clark, & Ashley, 2010), superior detection of a mistuned harmonic in a complex tone (Zendel & Alain, 2009), and better performance on musical imagery tasks (e.g., imagining and mentally comparing notes that accompany lyrics; Aleman, Nieuwenstein, Böcker, & de Haan, 2000). Musicians are also more sensitive to small duration changes (Musacchia, Sams, & Kraus, 2007), they more accurately synchronize their taps to the beat of music (Drake, Penel, & Bigand, 2000), and they show enhanced perception and production across a wider range of tempos and metrical levels than do nonmusicians, presumably because they possess more robust cognitive representations of the metrical hierarchy (Drake, Jones, et al., 2000; Jongsma, Desain, & Honing, 2004). Conductors readily detect deviant auditory stimuli presented in their periphery, whereas solo instrumentalists and nonmusicians show a marked decline for peripherally versus centrally presented targets (Münte, Kohlmetz, Nager, & Altenmüller, 2001). This pattern of results suggests that specific aspects of music training—such as tracking and controlling sound that is spatially distributed—are associated with relevant enhancements in perception.

Accompanying these behavioral differences in performance are striking anatomical and functional differences between the brains of musicians and nonmusicians. When compared with nonmusicians, musicians have enlarged gray matter in auditory cortex (Schlaug, Jäncke, Huang, & Steinmetz, 1995; Schneider et al., 2002) and multimodal integration areas (Bangert & Schlaug, 2006; Gaser & Schlaug, 2003; Sluming et al., 2002), as well as enlarged fiber tracts such as the corpus callosum, which plays a role in interhemispheric communication (Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995), and the arcuate fasciculus, which connects brain regions involved in sound perception and control of vocal production (Halwani, Loui, Rüber, & Schlaug, 2011). Musicians' and nonmusicians' brains have been compared by using functional brain imaging techniques such as fMRI and magnetoencephalography (MEG), and these studies reveal that music training is associated with enhanced responses over a wide network of auditory (Koelsch, Gunter, Wittfoth, & Sammler, 2005; Ohnishi et al., 2001), sensorimotor (Elbert, Pantev, Weinbruch, Rockstroh, & Taub, 1995; Hund-Georgiadis & von Cramon, 1999; Lotze, Scheler, Tan, Braun, & Birbaumer, 2003; Pantev et al., 1998), and frontal (Bangert et al., 2006; Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005; Sluming, Brooks, Howard, Downes, & Roberts, 2007) brain areas.

With its superior temporal resolution, techniques such as MEG and EEG can shed light on how musicians and nonmusicians process musical structures as they unfold over time. For example, single pure or instrument tones elicit auditory evoked potentials (such as P1, N1, and P2) that are larger or earlier in musically trained than untrained listeners (Pantev et al., 1998; Shahin, Bosnyak, Trainor, & Roberts, 2003; Shahin et al., 2004; Tervaniemi et al., 2005; Zendel & Alain, 2009). The mismatch negativity (MMN for EEG and MMNm for MEG) is another early brain response that can be elicited when an unexpected event or pattern is presented. Compared with nonmusicians, musicians exhibit larger MMN responses to subtle pitch and duration deviants in sequences of identical tones (Marie, Kujala, & Besson, 2012). Musicians also show larger MMN responses to interval or contour changes in a melody (Fujioka et al., 2004), pitch deviants in one of two simultaneous melodies in a polyphonic context (Fujioka et al., 2005), unexpected chords within a chord sequence (Brattico et al., 2009), violations to the rhythm and meter of a drum sequence (Vuust et al., 2005), omissions within a periodic tone sequence (Rüsseler, Altenmüller, Nager, Kohlmetz, & Münte, 2001), and changes in the number of events comprising a rhythmic group (van Zuijen, Sussman, Winkler, Näätänen, & Tervaniemi, 2005). Musicians' MMN responses to deviants in musical contexts also have a lower threshold for elicitation than nonmusicians' responses have. For example, while a small mistuning in a chord sequence elicits an MMN response in professional violinists, the mistuning must be considerably larger to elicit an MMN in nonmusicians (Koelsch, Schröger, & Tervaniemi, 1999). Likewise, ERP responses to pitch deviants in a sound field reveal superior auditory-spatial tuning among conductors in comparison with nonmusicians (Münte et al., 2001). Musicians' brains also reveal enhanced responsiveness to violations of expectancy in the context of large-scale musical structure such as tonality and meter. Compared with nonmusicians, musicians exhibit larger late brain responses to violations of harmonic expectation within a chord sequence (Koelsch, Schmidt, et al., 2002). Similarly, musicians (drummers and bass players) show enhanced P3 responses to occasional probe events within a metrical context (Jongsma et al., 2004) and to omissions in rhythmic sequences (Jongsma et al., 2005), suggesting that they have enhanced neural processing of musical meter. Finally, induced gamma band activity, which indicates synchronous activity over distributed cortical areas and higher cognitive functions, is enhanced among musicians (Bhattacharya, Petsche, & Pereda, 2001; Shahin, Roberts, Chau, Trainor, & Miller, 2008).

Recent evidence suggests that enhancements related to music training even extend to the brain stem. The auditory brain stem response (ABR) entrains to periodicities in auditory stimuli, and the correlation between the response and the stimulus can provide an index of how precisely pitch is encoded in the brain stem (Kraus & Chandrasekaran, 2010). In these studies, musicians exhibit an earlier brain stem response to cello notes (Musacchia et al., 2007) and more precise encoding of the upper tone in two-tone intervals as well as frequency components that reflect interaction of the two tones (such as combination tones and temporal envelope), than do nonmusicians (Lee, Skoe, Kraus, & Ashley, 2009). Given that the upper voice in a polyphonic context typically carries the melody, enhanced processing of these tones is consistent with the notion that musicians are more sensitive to structures that are important in music (Fujioka et al., 2005; Lee et al., 2009).

To summarize, an abundance of neural and behavioral evidence converges in showing that adult musicians enjoy enhanced processing of a wide range of musical structures, from single notes to rhythm and meter to harmony.

B. Does Music Training Cause Enhanced Processing in Adults?

It is tempting to assume that the observed behavioral and neural enhancements just described are the result of music training. However, a pervasive criticism of this literature is that few studies use adequate controls to determine whether music lessons lead to enhanced abilities or preexisting enhanced abilities lead individuals to take music lessons. For example, children of musicians, who are likely to have a genetic predisposition for music, are more likely to be encouraged to take music lessons and are more likely to continue music training for longer periods. If basic hearing abilities are heritable, as indicated by the finding that pitch discrimination ability is more similar in monozygotic than dizygotic twins (Drayna, Manichaikul, De Lange, Sneider, & Spector, 2001), then individuals with superior pitch processing might be more drawn toward music than individuals with inferior pitch processing. Unfortunately it is often difficult to control for preexisting differences between musicians and nonmusicians, such as basic hearing abilities, socioeconomic status, intelligence, talent, motor skills, motivation, discipline, and self-control.

Several findings are nevertheless consistent with the notion that music training drives neuroplasticity in adult musicians. First, neural enhancements among musicians have been shown to be specific to the instrument of practice. For example, violinists exhibit larger brain responses to violin sounds than to trumpet sounds, and trumpet players show larger responses to trumpet than to violin sounds (Pantev, Roberts, Schulz, Engelien, & Ross, 2001). Likewise, gamma-band activity in violinists is enhanced for violin sounds (Shahin et al., 2008). Unless musicians possess musical predispositions prior to training that involve specific instruments or specific types of musical training (e.g., Münte et al., 2001), such evidence would suggest that the brain changes in response to these specific experiences.

A second finding is that the amount of music training or practice often positively predicts the size of behavioral and neural enhancements. For example, years of formal music lessons are correlated with performance on psychophysical tests such as temporal order judgments and pitch discrimination (Jakobson, Cuddy, & Kilgour, 2003). Years of playing an instrument is a predictor of the extent to which gray matter is enhanced in musically relevant brain areas (Schneider et al., 2002; Gaser & Schlaug, 2003; Sluming et al., 2002, 2007), and the latency and precision of brain stem responses to sounds (Lee et al., 2009; Musacchia et al., 2007). The age of onset of music lessons also appears to be important, with those beginning lessons earlier showing larger responses (Amunts et al., 1997; Elbert et al., 1995; Ohnishi et al., 2001; Pantev et al., 1998; Schlaug, Jäncke, Huang, Staiger, et al., 1995; Trainor, Desjardins, & Rockel, 1999; see Chapter 14, this volume, for further discussions).

A final observation is that short-term training of nonmusicians can produce enhancements that resemble those observed in adult musicians. For example, after nonmusicians are trained to discriminate sounds in the laboratory, they exhibit enhanced auditory evoked potentials such as the P2 (e.g., Bosnyak, Eaton, & Roberts, 2004; Shahin et al., 2003; Tremblay, Kraus, Mcgee, Ponton, & Otis, 2001). Similarly, after learning to play a keyboard melody for 2 weeks, nonmusicians showed an enhancement of the MMN response to wrong notes in chord sequences, whereas nonmusicians in a yoked control condition who only heard and made judgments about the practice sessions of participants in the other group did not show this enhancement (Lappe, Herholz, Trainor, & Pantev, 2008). Similar effects have been shown for learning to play rhythmic patterns (Lappe, Trainor, Herholz, & Pantev, 2011). Although training in the laboratory presumably differs from the experience of taking formal music lessons, such findings indicate that controlled manipulation of experience can lead to neuroplastic changes in auditory brain responses.

Together, the above observations undermine the notion that preexisting abilities or talents can account for the observed behavioral and neuroanatomical differences between adult musicians and nonmusicians, at least for enhancements of music processing. Nevertheless, developmental research is necessary to definitively determine the effects of music training during childhood.

C. Effects of Formal Music Training on Musical Development

Like adult musicians, children taking music lessons exhibit superior music-related perception and production compared with children who are not taking music lessons. For example, children between 8 and 11 years of age learning to play a musical instrument outperform age-matched controls at identifying the contour of a melody (Morrongiello & Roes, 1990), detecting pitch incongruities at the end of musical phrases (Magne, Schon, & Besson, 2006), performing a complex motor sequence, discriminating simple melodies, and detecting pitch and rhythm changes in standardized tests of audiation (Gordon Test; Forgeard, Winner, Norton, & Schlaug, 2008). Between 6 and 10 years of age, child musicians more accurately synchronize their tapping to isochronous and rhythmic tone sequences and to orchestral music, and they can tap at slightly slower tempos and higher levels of the metrical hierarchy than can their nonmusician peers (Drake, Jones, & Baruch, 2000). However, it is still possible that preexisting differences can account for these effects.

Longitudinal behavioral studies have provided stronger evidence that formal music training is associated with gains in music perception and production skills. For example, one study measured performance on a standardized test of tonal and rhythmic discrimination among 5-year-olds before and after they participated in one of three conditions: (1) musical instrument training, (2) music classes with an emphasis on singing, playing drums, and dance, or (3) no training (Flohr, 1981). After 12 weeks, discrimination performance improved for both of the music instruction groups but not for the group receiving no training. Another study found that after one year of Kodaly instruction (which emphasizes rhythm and movement), 6-year-olds were more accurate at synchronization and continuation tapping than were their 6-year-old peers who received the standard music appreciation curriculum (Hurwitz, Wolff, Bortnick, & Kokas, 1975). Similarly, after 9 months of participation in group music classes, 5-year-olds outperformed a control group on musical skill improvements such as keeping a steady beat, rhythm reproduction, and vocal pitch matching (Bilhartz, Bruhn, & Olsen, 1999). Results of a more recent longitudinal study indicated that after 15 months of music lessons, 6-year-olds outperformed a nonmusician control group on motor sequencing and rhythm and pitch discrimination tasks, even though no group differences had been apparent before the lessons (Hyde et al., 2009). Music lessons are thus predictive of behavioral improvements in music perception and production during childhood.

Anatomical brain differences related to music training are also evident during childhood. One study used MRI to compare the brains of 5-year-old children who were about to begin taking music lessons with control children who were not, and reported no group difference before the onset of music lessons (Norton et al., 2005; Schlaug et al., 2005). However, after 15 months, children taking music lessons already showed anatomical changes consistent with those observed in adult musicians, with increased volume in the right primary auditory region, motor areas, and corpus callosum, all of which correlated with improvements in behavioral measures of melody and rhythm processing (Hyde et al., 2009). Although children were not randomly assigned to the music or control group, the absence of brain differences before the music lessons strongly suggests that the observed brain changes resulted from the 15 months of music training.

Like adult musicians, children taking music lessons exhibit enhanced brain responses to musical stimuli across a range of complexity levels. When presented with isolated tones, the early ERP responses of 4- to 5-year-olds who have completed 1 year of music lessons are similar to ERPs of nonmusician children 3 years older (and unlike responses of same-age nonmusician controls), suggesting that music lessons and enriched auditory experience might effectively speed up the development of early auditory evoked potentials (Shahin et al., 2004). Gamma-band activity, which is linked to top-down processes such as attention and memory, also showed greater increase in the same children after a year of lessons, whereas controls showed no changes in gamma-band activity (Shahin et al., 2008). This result is consistent with the finding that 4- to 6-year-old children receiving music lessons show a greater change over the course of a year in magnetic evoked responses to isolated violin tones (Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006).

Music lessons may also enhance children's brain responses to violations of musical phrase structure, contour, and harmony. When presented with short musical phrases that occasionally ended with small or large pitch shifts, 8-year-old musically trained children exhibited larger ERP (N300) responses than their nonmusician peers to small pitch incongruities, whereas both groups exhibited similar ERP responses to large pitch incongruities (Magne et al., 2006). Using a similar approach, older children (11−14 years) were presented with short melodies that were occasionally replaced with altered melodies having "slight" or "extreme" errors that either maintained or violated the original melodic contour and key (Wehrum et al., 2011). Similar to the Magne et al. (2006) finding, musically trained but not untrained children exhibited stronger responses to "slight" errors, whereas both groups showed increased activation to "extreme" errors. However, it is unclear whether the brain responses were due to contour or key violations or both, because contour and key errors were presented simultaneously. There is evidence that compared with nonmusicians, the brains of musically trained children are more sensitive to harmony, as shown by the finding that amount of music training (none, moderate, or extensive) is predictive of the size of brain responses to unexpected chords (i.e., chords that violate expectations for a typical harmonic progression) over auditory and frontal brain areas in 10-year-olds (Koelsch, Fritz, et al., 2005). A similar study showed that the amplitude of an ERP response (the early right anterior negativity or ERAN) to unexpected chords was more than twice as large in musically trained than untrained 10-year-olds (Jentschke & Koelsch, 2009).

Quasi-experimental designs such as those just described are helpful for showing that enhancements arise after but not before training, and this lends further support to the notion that music training changes the brain. The gold standard for inferring causality, however, is to use random assignment when possible, because preexisting differences, although not measurable before training, might lead some children to pursue and continue lessons and others to drop out. In one such study, 8-year-old Portuguese children were randomly assigned to 9 months of music or painting classes, both of which were highly engaging, had similar demands, and were comparably structured (e.g., both groups had a recital or exhibit at the end of the training period; Moreno et al., 2009). Echoing prior studies that did not use random assignment (Magne et al., 2006), phrase-final pitch incongruities in melodies elicited an ERP (N300) response that was enhanced after training in the music group only. Because children had an equal chance of being assigned to painting or music lessons, posttraining group differences strongly support the claim that music lessons cause training-related enhancements.

The effects of music lessons on musical development have been investigated primarily with children who are at least 5 years of age. This is because children rarely begin to learn to play a musical instrument before this age. However, in recent years there has been a proliferation of music programs for infants and toddlers and their parents (e.g., "mommy and me" music classes). Such programs differ markedly from learning to play a musical instrument, but they nevertheless provide musical enrichment in the form of music listening, singing, and movement. It is therefore reasonable to ask whether or not participation in such activities leads to enhancements or changes in the development of musical skills. One such study compared rhythm and meter perception among 7-month-old infants who were or were not enrolled in Kindermusik classes (Gerry et al., 2010). Kindermusik classes expose infants to a broad repertoire of Western musical pieces with predominantly duple metrical structures, which means that infants taking these classes presumably had more experience hearing and moving in time with duple than with triple meters. During testing, infants in both groups were presented with ambiguous rhythms and bounced to every other event (a duple meter) or every third event (a triple meter), and in a subsequent test phase they were played unambiguous (amplitude accented) versions of the same rhythm that either did or did not match the bouncing they had experienced (cf. Phillips-Silver & Trainor, 2005). Compared with control infants, infants enrolled in Kindermusik not only listened longer to the test stimuli, suggesting greater engagement with the rhythms, but they also exhibited a duple-meter bias, with larger familiarity preferences observed when infants were bounced to duple than to triple meter. Because infants in the control group did not show this bias, this result suggests that participation in Kindermusik classes, and by extension, greater exposure to duple than triple meters in music, influenced infants' metrical processing and preferences. Gerry et al. (2012) have shown effects of infant musical training on the development of sensitivity to tonality. Infants in this study were randomly assigned at 6 months of age to either 6 months of an active Suzuki-based weekly class or 6 months of a passive music listening class. At 12 months, those in the active class preferred to listen to a tonal over an atonal version of a sonatina whereas those in the passive class showed no preference. Given the increasingly obvious influence of early experience on adult knowledge and abilities (Meltzoff, Kuhl, Movellan, & Sejnowski, 2009), further research is needed to fully understand the effects of musical enrichment during infancy and toddlerhood.

The popularity of music programs directed at very young children may arise from the widely held assumption that when it comes to learning music, earlier is better. Like language and many other domains (Hernandez & Li, 2007), younger learners may have an advantage over older learners for acquiring musical expertise. Despite the popularity of this idea, relatively few studies provide direct empirical support for it. One source of evidence comes from the literature on absolute pitch, which suggests that early music training (before the age of 7) is essential for acquiring absolute pitch at least among speakers of a nontonal language (Deutsch et al., 2006; Miyazaki & Rakowski, 2002; Takeuchi & Hulse, 1993). A second source of evidence comes from several of the studies (just discussed) comparing adult musician and nonmusician brains, which reveal that the age at which musicians began taking music lessons is negatively correlated with enhancements of cortical volume and the size of brain responses, suggesting that enhancements are larger for those who began music lessons at a younger age (Amunts et al., 1997; Elbert et al., 1995; Ohnishi et al., 2001; Pantev et al., 1998; Schlaug, Jäncke, Huang, Staiger, et al., 1995; Trainor, Desjardins, & Rockel, 1999; although see Sluming et al., 2002). Such findings are difficult to interpret, however, because the age of onset of music training is often confounded with total amount of training (in years). In other words, individuals who begin music lessons at a young age typically have more music training than individuals who begin later. Recent evidence suggests that even when total amount of music training (in years) is controlled, early-trained musicians (who began lessons before the age of 7) outperform late-trained musicians on synchronization to a complex visual rhythm (Watanabe, Savion-Lemieux, & Penhune, 2007) and reproduction of auditory rhythms (Bailey & Penhune, 2010). Such findings are provocative because they imply that there might be a sensitive or critical period for acquiring musical expertise (Hernandez & Li, 2007). However, there are other reasons that early music training might yield different results than later training. In comparison with music lessons for older children and adults, music lessons for young children may differ in content, approach, structure, and intrinsic appeal. Moreover, practice patterns may differ for younger and older learners, particularly because parents are able to exert more control over younger than older children. There may also be preexisting differences that determine whether children begin taking music lessons earlier or later. It is thus essential for future work to carefully control for factors unrelated to age to more thoroughly understand potential age-of-onset effects for music learning.

D. Conclusions

In this section, we have reviewed the rapidly expanding empirical support behind the claim that formal music instruction results in dramatic changes to musical perception and production abilities and their neural correlates. It is nevertheless important to also ask whether or not these abilities differ qualitatively from those acquired through everyday exposure to music, participation in singing and dancing, and other types of informal music making. Despite the music training-related enhancements reported in the literature, other studies find that musicians and nonmusicians process musical structures similarly. For example, several of the studies comparing musicians and nonmusicians showed no group differences for brain responses to some violations of musical structure (Magne et al., 2006; Marie et al., 2012; Wehrum et al., 2011). Behavioral studies using implicit tasks (which do not depend on the explicit knowledge that is typically emphasized in music training) have revealed comparable sensitivity to fundamental components of musical structure such as theme and variations, harmony, and tonality (Bigand & Poulin-Charronat, 2006; also see Honing, 2011). Given that dancing and movement to music are some of the most universal aspects of human behavior, it is not surprising that nonmusicians and musicians often exhibit no differences in their responses to rhythm and meter (Geiser, Ziegler, Jäncke, & Meyer, 2009; Snyder & Krumhansl, 2001; Ullal et al., under revision; van Zuijen et al., 2005). Some evidence suggests that listening habits (i.e., individual differences in genre preferences) are more predictive than formal training on expressive timing perception (Honing & Ladinig, 2009). This raises important questions about the nature of musical experience and its benefits. Musicians might simply amass more musical experience than nonmusicians, but the key elements of that experience might be accessible with or without formal training and thus extend to all listeners. On the other hand, if music is so natural and universal, we might ask why it is so challenging to learn to play an instrument (Marcus, 2012). Although some musical capacities are acquired readily through everyday listening experience, such as the ability to predict and form expectations about future events in a piece of music, it is undeniable that other musical skills, such as learning to read musical notation and coordinate it with specific finger movements, require tremendous amounts of time, concentrated effort, and self-discipline. Perhaps the technology of performing music places distinct demands on the learner that may involve high-level cognitive functions, such as those reviewed next. Research on the effects of different types of musical experience is therefore crucial to unlocking puzzles about the effects of music training.

VI. Interactions between Music Experience and Nonmusical Abilities

As a highly complex and communicative system, musical activities not only involve structured sound, but also rich experience across multiple sensory modalities. In the course of learning a particular music instrument or skill, individuals must learn about sound, touch, motor coordination, vision, memory, attention, and self-control. The evidence reviewed in Section V suggests that the hours spent practicing ultimately lead to better performance in both child and adult musicians on tasks that have obvious relevance for music. A more controversial question is whether or not music training and music experience give rise to enhancements outside the domain of music. This question has particular developmental importance because individuals typically begin music training during childhood, when any advantages would be expected to have potentially large, cascading effects. In this section, we review evidence related to the question of whether music training can cause "far transfer" of enhancements to nonmusical domains such as math and spatial skills, language, reading, and higher-level functions such as intelligence and executive functioning (see also Chapter 12, this volume).

A. Music and Mathematics

Teachers, parents, and journalists often assume that music and mathematics are interrelated and, likewise, that musical training can improve math skills, particularly among children. Because learning rhythmic and metric structure and notation necessitates a basic grasp of division, multiplication, and ratios, it seems reasonable to propose that music lessons might provide an opportunity to enhance learning of these mathematical concepts. To date, however, little empirical evidence supports a link between music and math.

Brain imaging evidence (fMRI) suggests that musician and nonmusician adults exhibit different activation patterns while doing mental addition and subtraction, for example, with musicians showing greater activation of areas involved in visual perception and analysis of shape information (left fusiform gyrus), working memory (prefrontal cortex), and decreased activation in visual association areas (Schmithorst & Holland, 2004). Such differences are suggestive but difficult to interpret, particularly in the absence of behavioral measures of math performance and ability. A developmental study measured mathematical ability in 6-year-old public school children who were assigned to a "test arts" classroom, which emphasized sequenced skills through a combination of Kodaly music instruction and painting, or a "standard arts" classroom following the standard curriculum, which also included music and painting (Gardiner, Fox, Knowles, & Jeffrey, 1996). After 7 months, children in the test arts classroom showed greater improvements in their standardized math scores than did the children in the standard curriculum. Although intriguing, it is unclear that music training per se drove the observed changes in math performance, because (1) both classrooms had some type of music instruction, (2) the experimental classroom received training in both musical and visual arts, so contributions of musical versus visual arts training was unclear, and (3) no measures were taken to control for potential differences in teaching quality, teacher motivation and enthusiasm, or students' awareness that they were or were not part of a "special" class (which could have led to a Hawthorne effect). A later meta-analysis revealed only weak effects of music training on math ability, with the majority of published studies reporting null effects (Vaughn, 2000). Thus, the widely assumed link between music and mathematics has not been supported by controlled, empirical studies.

B. Music and Spatial Abilities

As with music and math, much speculation has surrounded the question of potential links between music training and spatial abilities. A now infamous example is the so-called *Mozart effect*, where college students exhibited short-term increases in performance on standardized tests of spatial abilities after 1–5 days of brief exposure to a Mozart sonata (Rauscher, Shaw, & Ky, 1993, 1995). The researchers proposed that because similar spatial-temporal firing patterns characterize neurons over large expanses of cortex, listening to music might organize firing patterns in adjacent (right hemisphere) brain areas such as those involved in spatial processing and thus lead to spatial enhancements (Rauscher et al., 1993). Although the short-term effects of listening to Mozart were later shown to be due to mood and arousal (and could be just as readily elicited by Mozart, another composer, or a story; Thompson, Schellenberg, & Husain, 2001), these studies did not rule out the possibility that long-term music training might enhance spatial abilities.

One meta-analysis reported that out of 15 studies on music training and spatial reasoning, only 5 showed spatial skill enhancements related to music training, and these enhancements were specific only to certain tasks such as the Object Assembly subtest of the Wechsler Intelligence Scale for Children (WISC), but not Raven's Matrices subtests, which are visual pattern completion tasks (Hetland, 2000). Later studies also reported no differences in spatial reasoning (as measured by Raven's Matrices) among adults who did or did not have prior music training, even when music training was extensive (>10 years; Franklin et al., 2008; Schellenberg & Moreno, 2010). Nevertheless, subsequent work reported that 8- to 11-year-old children who had taken music lessons for at least 3 years outperformed their nonmusician peers on the Raven's Standard and Advanced Progressive Matrices test, and duration of music training was correlated with task performance (Forgeard et al., 2008). Children in this study were not randomly assigned to the experimental or control groups, but because they showed no preexisting differences in spatial task performance (Norton et al., 2005), the observed pattern of change suggests that either music training caused the enhancements, or that preexisting differences arose gradually over the course of development (see Section V,D for a discussion).

One possibility is that when music training leads to spatial enhancements, it is because certain types of training involve an inherently spatial component, such as learning to read musical notation or attending to the movements and sounds of other musicians in an orchestra. Spatial task advantages have been reported for adult male orchestra musicians on numerous tests, such as the Benton judgment of line orientation (JOL) task and mental rotation (Sluming et al., 2002, 2007). This is consistent with the finding that conductors have superior auditory spatial sensitivity compared with both nonmusicians *and* solo instrumentalists (Münte et al., 2001). Thus, learning to play in or conduct an orchestra may hone sensitivity to spatial information because of the spatially distributed nature of the ensemble. In a similar vein, because music notation depends on mastery of spatially distributed symbols and lines, learning to read music might train (or depend on) a domain-general set of spatial skills. Forgeard et al. (2008) reported no differences on spatial tasks between children enrolled in two contrasting types of music training (traditional vs. Suzuki, the latter of which involves a delay in learning music notation). However facility with music notation, such as sight-reading fluency, was not measured, nor were data reported separately for children learning to perform solo versus in an ensemble. If spatial enhancements arise from concretely spatial aspects of music training, we might ask whether or not such transfer effects should be considered "near" or "far." In either case, developing specific hypotheses about which types of musical experience should or should not lead to enhancements in spatial abilities might help interpret the undeniably mixed evidence on the relationship between spatial abilities and music training.

C. Music and Language

Excitement and speculation have surrounded the question of whether or not music and language rely on overlapping or distinct cognitive abilities and neural processes. On the one hand, double dissociations of music and language have been observed, where impaired musical abilities accompany intact language processing and vice versa (Peretz et al., 1994; Peretz & Hyde, 2003, but see Patel, Foxton, & Griffiths, 2005). Such cases have fueled speculation that music and language rely on separate, domain-specific neural architectures evolved for distinct functions in human life (Peretz & Coltheart, 2003). On the other hand, the two domains have striking similarities. Music and language are human cultural universals, and both consist of complex and dynamic acoustic information, contain rich and varied patterns of rhythm, pitch, timbre, dynamics, and phrasing, and are governed by rules that specify the arrangement of individual elements into higher-order hierarchical structures (McDermott & Hauser, 2005; Patel, 2008). It therefore makes sense to posit that language and music processing might rely to a large extent on the same cognitive and neural mechanisms.

Considerable recent evidence has suggested that certain regions of the brain support music *and* language processing, even at high structural levels such as tonality and syntax. For example, violations of language or music syntax (such as grammatical errors or out-of-key chords) both elicit modulations of the P600 event-related potential (Patel, Gibson, Ratner, Besson, & Holcomb, 1998). The inferior frontal gyrus (which includes Broca's area), considered to be a "classic" language area of the brain, responds to violations of both linguistic *and* musical syntax (Knoesche et al., 2005; Koelsch, Schmidt, et al., 2002; Maess, Koelsch, Gunter, & Friederici, 2001; Tillmann, Janata, & Bharucha, 2003). Comprehension of nonlocal dependencies within sung sentences is impaired if key words are sung to out-of-key notes, suggesting that musical and linguistic integration processes interact (Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009). Similarly, in a self-paced reading task where chords accompany each word of a sentence, unexpected chords enhance garden path effects (which involve syntactic integration) but do not interact with semantic violations (Slevc, Rosenberg, & Patel, 2009). Together, these brain and behavioral findings appear to support the "shared syntactic integration resource hypothesis" (SSIRH), which proposes that the online computation of syntactic structure in language and music relies on the same underlying process (Patel, 2003).

Music can also interact with semantic aspects of language processing. In a basic semantic priming paradigm, listeners are presented with a sentence or word followed by a target that can be semantically related or unrelated, and the unrelated target typically elicits slower reaction times and a larger N400 brain response. The semantic priming paradigm can be adapted for use with programmatic excerpts of purely instrumental music, for example Beethoven's Eroica Symphony, which evokes the semantic concept "hero." Just like linguistic primes, musical primes give rise to larger N400 responses to semantically unrelated linguistic targets (such as the word "coward"; Koelsch et al., 2004), and the reverse is found when linguistic primes precede 1-s musical targets (Daltrozzo & Schön, 2008). Even simpler musical stimuli can prime positively or negatively valenced words, for example consonant and dissonant chords, major and minor triads, or harsh and smooth timbres (Steinbeis & Koelsch, 2010). Thus, multiple studies suggest that brain responses thought to reflect syntactic or semantic processes in language are also elicited by musical stimuli.

The question of overlap in neural processing of language and music remains hotly debated. One problem is that so-called "language-specific" brain areas, such as Broca's, are not fully understood, and these areas may turn out to play a more domain-general role than previously assumed in a range of sequential processes (Rogalsky & Hickok, 2011). If true, this would not necessarily undermine the notion of language-specific circuits in the brain, given evidence that even the same auditory stimulus (sine wave speech) can elicit both "speech-specific" patterns of neural response and domain-general responses depending on whether or not the listener perceives it to be speech or nonspeech (Möttönen et al., 2006). Recently it has been shown that music and speech activate topographically overlapping brain regions, but that the pattern of activation within those areas differs for music and speech stimuli, such that brain activity on individual trials can be reliably classified as arising from either speech or music, and manipulations of music and language structure elicit distinct, domain-specific changes in the brain response (Abrams et al., 2011; Rogalsky, Ron, Saberi, & Hickok, 2011). Thus, evidence of mere overlap in brain regions activated while listening to music and speech may not be sufficient to support the claim that the same underlying processes and mechanisms operate in both domains.

1. *Influence of Music Experience on Language Abilities*

Cross-domain transfer effects would provide additional support for claims of shared representations and mechanisms for music and language. If the same cognitive and neural processes are involved in both music and language, then musical experience might be expected to transfer to language and, likewise, language experience might be expected to transfer to music. One strategy for addressing this question is to compare the language abilities of musicians and nonmusicians. This research has generally suggested there are robust differences between how musicians and nonmusicians process language at multiple structural levels and among listeners of various ages.

Given that music and language sequencing and syntax appear to involve overlapping brain regions and responses, it is perhaps not surprising that music training is associated with enhanced sensitivity to sequential and syntactic structure in language. For example, in a segmentation procedure in which listeners were presented with a continuous sequence of sung syllables containing certain predictive regularities, professional musicians subsequently showed larger ERP responses than did nonmusicians to violations of those regularities (i.e., to "nonwords"), whether those violations involved syllable or tone regularities (Francois & Schön, 2011). This finding suggests that musicians are better at discovering patterns within novel sequential auditory stimuli, whether linguistic or musical. If children taking music lessons are better general statistical learners, child musicians might be expected to grasp language structures earlier in development than would child nonmusicians. Indeed, even though children who were or were not planning to take music lessons had comparable language abilities before taking music lessons (Norton et al., 2005), after 18 months of music training, children taking music lessons outperformed their peers on a vocabulary test (defining words) (Forgeard et al., 2008). Compared with 10-year-olds who were enrolled in regular public school, 10-year-olds enrolled in public music school and the St. Thomas Boys Choir exhibited more mature (i.e., larger amplitude) brain responses to violations of harmonic structure in music *and* syntactic structure in language (Jentschke & Koelsch, 2009). Thus, children enrolled in music lessons appear to grasp high-level aspects of language structure earlier in development.

Formal music training is also associated with enhanced verbal memory. For example, musicians are better than nonmusicians at recalling previously presented poetry or song lyrics (Kilgour, Jakobson, & Cuddy, 2000). Musicians outperform nonmusicians on a range of standardized verbal memory and verbal working memory tasks (Brandler & Rammsayer, 2003; Franklin et al., 2008; Jakobson et al., 2008), and scores on the Logical Memory Stories subtest of the Wechsler Memory Scale are positively predicted by number of years of formal music training (Jakobson et al., 2003). These advantages may be limited to verbal memory tasks, as shown by the finding that Chinese musicians outperform nonmusicians on a verbal memory test (Hong Kong List Learning Test) but not on a visual memory test (Benton Visual Retention Test), even though both tests require participants to identify as many items as possible from a previously presented set of items (Chan, Ho, & Cheung, 1998). This general trend is also observed in children aged 6 to 15 years, whose duration of music training positively predicts their verbal memory scores, even after age and education level are controlled for (Ho, Chueng, & Chan, 2003). Even after being randomly assigned to as little as 4 weeks of music lessons, 4- to 6-year-old children show enhanced verbal but not spatial IQ (Moreno et al., 2011). However, other studies using American participants have reported that musicians outperform nonmusicians on both verbal *and* visual memory tasks (Jakobson, Lewycky, Kilgour, & Stoesz, 2008). One explanation for these contradictory results is that experience with an ideographic writing system such as Chinese might enhance visual memory for all Chinese participants, thus obscuring any advantages conferred by music training among Chinese but not American participants (Jakobson et al., 2008). Nevertheless, mental imagery tasks also support the notion that musicians have superior auditory but not visual abilities. When given a musical auditory imagery task (to imagine and compare musical notes that accompany familiar lyrics), a nonmusical auditory imagery task (to imagine and compare everyday sounds), and a visual imagery task (to imagine and compare objects), musicians outperform nonmusicians on both auditory imagery tasks but not on the visual imagery task (Aleman et al., 2000). This raises the possibility that the observed advantages arise not from specific transfer of music training to language ability, but rather domain-general enhancements of auditory working memory among musicians (see Section VI,D for further discussion).

Musicians are also particularly good at understanding speech presented in a noisy environment. When asked to repeat sentences embedded in varying amounts of background noise (using the Hearing in Noise Test), musicians are more accurate than nonmusicians, and individual scores are predicted by the duration (in years) of music training (Parbery-Clark, Skoe, & Kraus, 2009). Such effects arise as early as the brain stem. Background noise degrades the fidelity of pitch encoding in the brain stem of all listeners, but its degradative effects are attenuated for musicians (Parbery-Clark et al., 2009). Behavioral and brain stem enhancements are also evident in tasks that require musicians and nonmusicians to discriminate speech sounds under reverberation conditions ("dry" or no reverberation, mild, medium, and severe) (Bidelman & Krishnan, 2010). Psychophysical difference limens and brain stem encoding responses are more robust under reverberation conditions in musicians than in nonmusicians, particularly for encoding of formant-related harmonics (Bidelman & Krishnan, 2010). This finding suggests that musicians are better at tuning their attention to specific signals and disregarding irrelevant noise, whether those signals are musical or linguistic.

One of the related ways in which music training might be expected to influence language processing is in the area of speech prosody. Variations in intonation (fundamental frequency contour), rhythm, and stress are all aspects of speech prosody, the "musical" component of speech. It therefore makes sense that music training would hone a listener's ability to attend to the pitch and rhythm of speech. Consistent with this prediction, when asked to evaluate the pronunciation of words at the ends of sentences, musicians are more likely than nonmusicians to notice when the word is lengthened and the stress pattern disrupted, and they exhibit larger amplitude P200 brain responses to rhythmic violations than do nonmusicians (Marie, Magne, & Besson, 2010). Both behavioral and ERP responses reveal that musicians are also better than nonmusicians at detecting subtle intonation changes in speech utterances, even in the context of a language they do not know

(Marques, Moreno, Castro, & Besson, 2007). This trend is also evident in 8-year-old nonmusician children after being randomly assigned to painting or music lessons for 6 months. After training, children in the music group were more sensitive to subtle pitch incongruities in speech, while children in the painting group showed no improvements (Moreno & Besson, 2006; Moreno et al., 2009). Consistent with the behavioral and ERP evidence, musicians show a more accurate brain stem representation of the fundamental frequency of foreign speech (Bidelman, Gandour, & Krishnan, 2010; Wong, Skoe, Russon, Dees, & Kraus, 2007), and the amplitude of brain stem responses to speech is positively predicted by the duration (in years) of music training (Musacchia et al., 2007). It is perhaps for this reason that English-speaking musicians outperform English-speaking nonmusicians at learning to identify lexical tones in Mandarin Chinese (Lee & Hung, 2008; Wong & Perrachione, 2007).

If musicians are better at encoding pitch information in speech, it follows that they might also be better at interpreting emotional information from speech prosody. Musicians are in fact more accurate at identifying the emotional prosody of semantically neutral speech utterances, particularly for negative emotions (Thompson, Schellenberg, & Husain, 2004). Musicians also exhibit larger brain stem response magnitudes than nonmusicians when presented with emotional vocalizations (Strait, Kraus, Skoe, & Ashley, 2009). To summarize, the preceding evidence provides compelling support for the claim that music training may change and improve the encoding of pitch information in speech, and it may enhance musicians' ability to discern emotion in speech and to learn languages that employ pitch to communicate meaning.

2. *Influence of Language Experience on Musical Abilities*

Not only does musical experience influence language ability, but specific linguistic experience may also influence how an individual listener perceives music. For example, the temporal features of one's native language may influence how he or she perceives temporal information in musical contexts. When presented with a pattern of short and long durations (such as a short-short-long rhythm), native English-speaking adults and English-learning 8-month-olds are more likely to notice a duration increase to the short than to the long duration, presumably because they perceive a grouping boundary after the long duration (Trainor & Adams, 2000). Interestingly, among speakers of Japanese, a language that uses object-verb word order (instead of English verb-object order), this grouping tendency is not observed (Iversen, Patel, & Ohgushi, 2008). Such cross-cultural differences appear to emerge by 7–8 months of age, when English and Japanese infants exhibit opposite preferences for nonlinguistic rhythmic patterns that disrupt iambic versus trochaic grouping (Yoshida et al., 2010). It is nevertheless unclear from this work whether linguistic (and not musical) experience is responsible for cross-cultural differences. Assuming language is responsible, it would also be important to determine which aspects of language—word order, prosody, stress patterns, and so on—drive such effects.

Speech prosody is yet another potential route for language-to-music transfer. Linguists have classified languages according to their prosodic rhythms; for example, English is classified as a stress-timed language and French as a syllable-timed language. An acoustic correlate of rhythmic class is durational contrast (amount of variance in syllable duration), because stress-timed languages with vowel reduction, such as English, tend to have higher durational contrast than syllable-timed languages such as French. In this light, it is perhaps not surprising that orchestral themes written by English-speaking composers have greater note-to-note durational contrast than themes by French-speaking composers, suggesting that the composer's native language prosody leaves a rhythmic imprint on the instrumental music he or she composes (Patel & Daniele, 2003). These rhythmic differences do not simply exist in the music notation, but are perceived by listeners. For example, adult nonmusicians can accurately classify novel instrumental folk melodies according to language of origin (Hannon, 2009). Recent work even suggests that prosodic pitch patterns that vary by language (French vs English) are reflected in the melodic variability of music from those cultures (Patel, Iverson, & Rosenberg, 2006). Further research is needed to understand the extent to which experience with native-language prosody can transfer to the music domain, given that native-language prosodic features appear to exist in both the speech *and* music of a given culture.

Other evidence links the phonological properties of the native language with nonlinguistic auditory abilities relevant for music. For example, although vowels in languages such as English can vary freely in duration, languages such as Finnish and Japanese use duration contrastively, such that the meaning of an otherwise identical word can be altered by a small change in vowel duration. Although it is not surprising that speakers of Finnish and Japanese are more sensitive to vowel duration deviants, more surprising is the finding that duration deviants within melodic sequences are also better detected and elicit larger brain responses in native Finnish speakers than in French speakers (Marie, Kujala, & Besson, 2012). In fact, Finnish nonmusicians perform at par with French musicians, and both groups outperform French nonmusicians (Marie et al., 2012). Thus, expertise with one's native language can give rise to enhanced perceptual sensitivity to rhythmic features in both linguistic and musical contexts. This trend is also evident for pitch processing, which is enhanced among native speakers of a tone language such as Chinese. Mandarin-speaking adults outperform English-speaking adults in tasks of two-tone interval discrimination and reproduction of two- and four-note sequences, even when groups are matched for formal music training (Pfordresher & Brown, 2009). Chinese-speaking individuals also exhibit more faithful brain stem encoding of pitch, for both continuous frequency glides (which resemble a Chinese tone) *and* discrete pitches (an ascending major third in music; Bidelman et al., 2010). Again, brain stem response enhancements among native speakers of Chinese are comparable to those observed among English-speaking musicians, suggesting that language- and music-specific expertise give rise to similar pitch processing benefits.

It would thus appear that language-specific experience can transfer to the music domain, just as music-specific experience can transfer to the language domain. It is nevertheless important to keep in mind that transfer effects do not necessarily indicate uniform, domain-general pitch or rhythm abilities that are improved through experience in either domain. Rather, enhancements could be highly specific to the particular language or type of musical structures learned. Several recent findings support this hypothesis. For example, although the overall correlations between stimulus and brain stem responses are high among tone language users and musicians, closer examination of brain stem responses over the time course of the pitch glide stimulus reveals distinct patterns of enhancement for Chinese speakers versus musicians, with Chinese speakers optimally processing rapid frequency transitions and musicians optimally processing specific pitch regions corresponding to notes in musical scales (Bidelman et al., 2010). Moreover, despite their enhanced brain stem pitch encoding, Chinese nonmusicians do not necessarily outperform English-speaking nonmusicians on perceptual discrimination of complex musical patterns such as arpeggios, whereas trained musicians show both brain stem enhancements *and* improved behavioral performance (Bidelman, Gandour, & Krishnan, 2011). Similarly, in behavioral tasks Chinese speakers in fact show *impaired* detection of downward (but not upward) pitch changes, perhaps because Mandarin uses a larger pitch range for falling than for rising tones (Peretz, Nguyen, & Cummings, 2011). In conclusion, rather than indicating that language and music share the same underlying processes and mechanisms, building evidence suggests that cognitive and neural representations of music and language are integrally tied to the culture-specific systems that are acquired over the course of development. Perhaps when "domain-specific" brain and behavioral responses are observed, they at least partly reflect experience with specific languages and musical cultures. Cross-cultural, parallel investigations of music and language acquisition are thus key to better understanding the nature of music-language interactions.

3. *Music and Reading*

Reading ability has also been linked to musical competence. In a meta-analysis of 25 studies of reading and music training among children and adults, Butzlaff (2000) reported a significant association between music training and reading skills. As little as 1 year of Kodaly music instruction in the classroom is associated with gains in reading skill in 6-year-olds (Hurwitz et al., 1975). Eight-year-olds who were randomly assigned to music training (also using Kodaly and Orff techniques) outperform same-age peers assigned to visual arts training on reading tasks that measured comprehension of complex print-to-sound correspondence (Moreno et al., 2009). Given that both of these experiments provide children with music instruction that emphasizes rhythm, movement, and aural skills but *not* musical notation, this evidence suggests that music training-related gains in reading ability are not the result of learning to read music, but rather they are somehow linked to gains in rhythmic and/or pitch-based auditory and motor skills.

Links between reading and auditory rhythmic skills have also been found among individuals who have no formal music training. Musical aptitude predicts phonemic awareness and reading ability among 5-year-olds (Anvari, Trainor, Woodside, & Levy, 2002), verbal IQ among 10-year-olds (Lynn, Wilson, & Gault, 1989), and receptive and productive phonological proficiency among adults learning a second language (Slevc & Miyake, 2006). Notably, musical aptitude does not predict mastery of second language syntax or lexicon, but rather predicts only phonological skills (Slevc & Miyake, 2006). Some researchers have even used simple musical aptitude tasks such as pitch discrimination to forecast later reading ability in 4- and 5-year-old children, suggesting that such tests rival phonemic awareness tests in predicting later reading achievements (Lamb & Gregory, 1993). Detection of local but not global melodic contour change has also been associated with reading ability and phonological skill (speed and accuracy of word pronunciation) among college students (Foxton et al., 2003). Together, these studies indicate that there is something about the ability to parse and compare units of sound, whether linguistic or musical, that predicts reading ability.

An interesting parallel to the preceding findings is that children with reading or language impairments often suffer from nonlinguistic auditory deficits and decreased musical aptitude. Indeed, there is evidence that some (but certainly not all) children with language impairments exhibit impaired temporal processing; for example, they have difficulty accurately perceiving two briefly presented sounds in succession (Tallal & Gaab, 2006) and they have higher backward masking thresholds (i.e., they need a target tone to be much louder when followed by a competing noise; Wright et al., 1997). Children ages 7–11 diagnosed with speech and language impairments showed greater variability in synchronous tapping to a metronome when compared with age-matched peers, even though they showed normal performance when tapping a self-paced beat (Corriveau & Goswami, 2009). Dyslexic children in the same age range also showed impairments in a rise time discrimination task in which a sound with an amplitude modulation rate of 0.7 Hz could be perceived as a beat or as a sliding sound depending on rise time (Goswami et al., 2002). Performance on rise time perception tasks is correlated with performance on rhythm discrimination, and rhythm discrimination predicts unique variance in phonological and literacy measures (Huss, Verney, Fosker, Meed, & Goswami, 2011). Interestingly, children who teach themselves to read and are thus classified as "early readers" exhibit superior rise time discrimination compared with normal peers and dyslexics, suggesting that the correlation between rise time perception and reading skill applies to normal populations as well as those with developmental disorders (Goswami et al., 2002). Indeed, one study testing normal (nondyslexic) 7-year-old children found a correlation between an individual's phonemic awareness and the extent to which that participant's pitch perception was correlated with pitch production, even after music training and age were controlled for (Loui, Kroog, Zuk, Winner, & Schlaug, 2011).

It therefore appears that music-relevant abilities, such as rhythm and pitch perception and production, are associated with reading abilities in both normal and language- and reading-impaired populations, although the specific nature of these associations is unclear and impairments are probably heterogeneous in nature. A crucial question is whether or not music training might benefit those with language and reading impairments, as it appears to do for normal populations (e.g., Moreno et al., 2009; Tallal & Gaab, 2006). One study indicates that phonological training (such as rhyme judgment, syllable counting, and word repetition) can lead to behavioral and brain enhancements in speech processing among dyslexics (Santo, Joly-Potuz, Moreno, Habib, & Besson, 2007). Music training—particularly training that emphasizes rhythm, meter, and synchronization—might be an additional, highly engaging intervention for improving phonological and reading skills among dyslexics. Further research is needed to investigate the potential of music lessons and music-related activities for promoting reading skills.

D. Music and General Cognitive Abilities

Overall, the evidence just described suggests that the nature of the relationship between music training and nonmusical cognitive skills remains elusive. On the one hand, there is only minimal support for the notion that music training enhances mathematical or spatial abilities, particularly those unrelated to concrete aspects of music training. On the other hand, there is growing evidence that music and language are mutually influential. However, the mechanisms of music-language interaction are unclear given the wide range of structural levels involved (e.g., prosody, meter, syntax). Rather than influencing specific abilities, one proposal is that music training leads to global effects on cognitive functioning and that the many hours of concentrated music practice might enhance general intelligence or other domain-general cognitive functions like attention, working memory, and inhibitory control.

Given that spatial, mathematical, and verbal abilities are inconsistently associated with music training, it is reasonable to posit that perhaps music training influences general intelligence rather than its specific spatial, mathematical or verbal subcomponents. Although many of the studies reviewed include measures of general intelligence, these tests are often included to control for IQ rather than to focus on it as a dependent variable. As such, several studies report no relationship between music training and intelligence as measured by standard IQ tests with children (Ho et al., 2003; Moreno et al., 2009) or adults (Bialystok & DePape, 2009; Chan et al., 1998; Sluming et al., 2002). It has even been reported that highly educated nonmusicians show higher IQ scores than professional musicians (Brandler & Rammsayer, 2003) or musicians with more than 11 years of training (Schellenberg & Moreno, 2010). Nevertheless, music training has been shown to robustly predict both IQ and academic achievement among children and adults, particularly when music is a hobby (Moreno et al., 2011; Schellenberg, 2006, 2011). One explanation for this association is that children who are creative and high functioning are already more likely to begin and to continue music lessons than are other children (Schellenberg, 2011). Only a few experiments provide compelling evidence that music lessons actually *cause* increases in IQ scores. Schellenberg (2004) randomly assigned 6-year-olds to take music (keyboard or singing lessons), drama lessons, or no lessons for a period of 36 weeks, and IQ was measured before and after lessons. Significantly greater increases in full scale IQ were evident in children who had been assigned to music lessons, although these increases were less than half the size of IQ differences reported in other studies (Schellenberg, 2006, 2011). A similar study randomly assigned 4- to 6-year-olds to music or visual arts training, and found verbal enhancements only in the musically trained group (Moreno et al., 2011). Together, such findings suggest that music lessons can cause modest IQ increases, but preexisting IQ differences probably also play a role in determining which children do or do not pursue music training (see Schellenberg, 2011, for a discussion).

An alternative possibility is that music training indirectly modifies IQ through enhancements to "cognitive control" or "executive functioning," a loosely defined set of processes presumed to be involved in goal-directed planning and problem-solving, cognitive flexibility, inhibitory control, working memory, and selective attention. Musical skills such as imitation, transcription, and memorization probably depend on working memory and rehearsal skills, which are honed through music practice. Of the studies reviewed in Sections VI,A−C, many of the tasks that successfully demonstrate transfer of music training to other domains place demands on working memory and imagery/rehearsal strategies. For example, Chan et al. (1998) and Ho et al. (2003) required participants to remember words from a list, and Jakobsen et al. (2008) required participants to remember words and visually presented designs after a delay. Even after IQ is controlled for, musicians recall more items and they are better able to employ semantic clustering strategies to facilitate recall of both verbal and visual items (Jakobsen et al., 2008). Musicians' efficient use of rehearsal strategies is also evident in tasks where they must recall words from a previously presented list while also performing an articulatory suppression task (saying the word "the" between each word from the list; Franklin et al., 2008). Although musicians outperform nonmusicians in the standard version of the task (without articulatory suppression), when the articulatory suppression task is introduced, they perform similarly to nonmusicians (Franklin et al., 2008), suggesting that superior auditory rehearsal strategies might explain musicians' advantages on the verbal tasks reviewed in Section VI,C,1. This conclusion is corroborated by the finding that musicians are faster and make fewer errors than nonmusicians on an N-back task requiring participants to indicate whether a current item is the same as the previously presented item (one-back, lower working memory load) or the item before the previous item (two-back, higher working memory load; Pallesen et al., 2010). Moreover, fMRI reveals that musicians show greater activation than nonmusicians in working memory areas (posterior parietal cortex) and a higher correlation between such brain responses and the working memory load of the task (Pallesen et al., 2010).

Selective attention might also benefit from music training, given the importance of sustained, focused concentration on a specific sound or pattern despite the presence of other competing stimuli. When musicians and nonmusicians were given a battery of cognitive and perceptual tests, such as frequency discrimination, simultaneous and backward masking (the latter of which is thought to rely on cognitive rather than peripheral abilities), working memory (repeating a sequence in reverse order), and attention (i.e., go no-go tasks in which participants were instructed to respond to one auditory or visual cue but not another, depending on contextual cues), musicians showed faster reaction times and more accurate performance than nonmusicians, particularly for frequency discrimination, backward masking, and auditory (but not visual) attention tasks (Strait et al., 2010). Another study measured EEG while participants listened to a story presented on one side of the head while actively trying to ignore a competing story presented on the other side of the head (Strait & Kraus, 2011). The variability of the overall EEG response to a stimulus was lower when it was attended than when it was ignored; however, this asymmetry was evident only at prefrontal electrode sites among musicians, leading the authors to conclude that musicians may possess enhancements of top-down selective attention (Strait & Kraus, 2011). If true, this would also be consistent with findings, reviewed earlier, that musicians are better at perceiving speech in noisy situations (see Section VI,C,1).

One hallmark of cognitive control is the ability to initiate appropriate responses and inhibit inappropriate responses in a particular context. Tasks that measure this aspect of cognitive control, such as Simon or Stroop tasks, typically require a participant to make one response (such as pressing a button to indicate whether a target appears on the right or left side of a screen) in the context of conflicting or congruent information (e.g., arrows that point away or toward the target side). Participants typically exhibit slower reaction times when there is conflict between the correct response and a cue, but this cost is lower for young adults with extensive music training, for either spatial or auditory Stroop/Simon tasks, suggesting that music training may lead to improved cognitive control (Bialystok & DePape, 2009). Interestingly, bilingual young adults, who have extensive experience switching between different sets of linguistic rules and vocabularies, also exhibit enhanced performance on a spatial Stroop task, but musicians outperform even bilinguals on the auditory Stroop task (Bialystok & DePape, 2009). Another study measured ERPs while musically trained and untrained 4- to 6-year-old children performed a visual go no-go task, and found enhanced P2 responses on no-go trials among musically trained participants only (and not among those with visual arts training; Moreno et al., 2011). Such changes were evident after only 4 weeks of training and after children were randomly assigned to music versus nonmusic training, thus providing compelling evidence for the potential for music training to affect aspects of higher level functioning. However, other measures of cognitive control do not support the conclusion that music training bolsters executive functioning. When 9- to 12-year-old children were given a battery of classic tests of cognitive control, including digit span (which measures attention and working memory), Sun-Moon Stroop (a simple version of the task from Bialystok & DePape, 2009), Tower of Hanoi (a puzzle commonly used to assess problem-solving), and Wisconsin Card Sort (a test of cognitive flexibility and rule switching), there were no differences in performance between untrained children and those who had taken at least 3 years of music lessons, although IQ did differ robustly between groups (Schellenberg, 2011). In fact, the various cognitive control tests were poorly correlated with each other, suggesting that at least in this sample the cognitive control tasks did not measure a single, unified ability but perhaps a set of diverse processes all subsumed under the loose construct of cognitive control/executive functioning. However, given the similarities between the Stroop tasks used in both studies, it is surprising that Schellenberg (2011) did not replicate Bialystok and DePape (2009). Perhaps music training-related enhancements of behavioral measures of cognitive control may depend on more extensive music training, or perhaps they do not appear until adulthood. Further research is needed to better understand potential benefits of music lessons on cognitive control, given the tremendous success of other interventions aimed at improving cognitive control among young children (Diamond, Barnett, Thomas, & Munro, 2007).

E. Conclusions

Remarkable discoveries have been made in the past decade that are transforming our understanding of the relationship between musical abilities, experience, training, and other cognitive abilities. Although previous claims of a link between music and spatial or mathematical abilities have obtained only minimal support, a growing foundation of research supports the notion that specific musical experiences can affect language processing and vice versa. The question of whether or not there are domain-general benefits of music experience for cognitive control and intelligence are also important ones given the potential for educational interventions with enduring effects on human welfare. Research on interactions between music and other domains is important not only for understanding musical development, but also for understanding the extent to which the human mind has evolved for specific functions (such as music or language) and the extent to which it depends on specific experiences to shape and build knowledge over the course of development. Research on music development therefore has the potential to illuminate fundamental questions about human nature and the acquisition of knowledge and skills over ontogenetic and evolutionary time scales.

VII. General Conclusions

Musical behavior is complex and multifaceted, and music is part of an infant's world from the beginning. Across all cultures, caregivers use song to communicate affectively with their infants, and they intuitively tailor their singing style to accomplish goals such as calming a crying infant, putting an infant to sleep, or arousing an infant in play. Infants respond positively to such singing and in different manners to different styles of singing. The social bonds engendered by musical participation continue through childhood, such that as the ability to physically entrain to an external beat emerges, and engaging in joint music making with other people increases prosocial behavior between participants.

In order to engage in music making with others in a culture, children must learn the complex pitch and rhythmic structures of that culture. As with learning to speak a language, such enculturation occurs without formal training. The beginnings of musical specialization can be seen by the end of the first year after birth and continue well into childhood. At the same time, just as schooling enhances language skills, formal musical training enhances musical skills. Such effects can readily be seen in brain and behavioral differences in preschool children, and there is even evidence of experiential effects before one year of age. More controversial is evidence that musical training has benefits for other cognitive skills such as language, spatial ability, mathematics, and general intelligence.

The evolutionary origins of music remain controversial, but research is revealing that the ontological origins of music begin very early, originate in social interaction, involve learning complex pitch and rhythmic structure, and rely on culture-specific experience, such that it takes many years to become a fully enculturated listener.

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