Chapter 8
Development of Pitch and Music Perception

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1 Introduction

Music, like language, is found in all known human societies, past and present, and although music has some precursors that can be found in other species, it is a defining characteristic of the human species (Wallin et al. 2000). Although the perception of music has multisensory aspects (Thompson et al. 2005; Phillips-Silver and Trainor 2007), it is based in sound. The vibrations that give rise to music can be created by many different means, including striking percussion instruments, blowing resonating air columns in wind instruments, plucking and bowing strings under tension, and vibrating the vocal chords during singing. The boundary between sounds that are perceived as music and sounds that are not is fuzzy; indeed a definition of music remains elusive. However, the vast majority of music in the world involves spectral and temporal organizations that can readily be processed by the nervous system and for which specialized brain processing develops.

Although the evolutionary adaptive value of music remains controversial (McDermott and Hauser 2005; Trainor 2008a), even in modern societies people spend large amounts of time and money on music (Huron 2003), suggesting that it serves important functions. From a neurological perspective, music is an interesting stimulus as it activates many cortical areas, including sensorimotor systems (e.g., Grahn and Brett 2007; Zatorre et al. 2007), memory and cognitive systems (Koelsch and Siebel 2005; Janata 2009), and social/emotional areas (e.g., Blood and Zatorre 2001). Music appears to have a special relation with movement, as even passive listening activates motor areas (Grahn and Brett 2007), and the way people move can affect how the rhythm of a musical stimulus is interpreted (Phillips-Silver and

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Trainor 2005, 2007). From a cognitive perspective, there is evidence that superior musical skills are accompanied by higher IQ scores (Schellenberg 2005), better mathematical ability (e.g., Vaughn 2000), and enhanced language development (e.g., Anvari et al. 2002; Magne et al. 2006; Moreno and Besson 2006). Perhaps most intriguing are recent reports that music enhances social relationships. Children who have sung together while playing show more prosocial behavior than children who have simply played together (Kirschner and Tomasello 2010). Even in infancy, music is used for social/emotional communication (Trehub 2009). Singing to infants is universal across cultures (Trehub and Trainor 1998), and infants prefer the loving tone of voice and friendly higher pitch of infant-directed compared to non-infant-directed singing (Trainor 1996; Trainor and Zacharias 1998). Indeed, caregivers use singing to achieve various parenting goals. The soft, slow, airy, low-pitched characteristics of lullabies put infants to sleep and the fast, high-pitched, rhythmic characteristics of play songs rouse infants and encourage them to engage in social interaction (Trainor et al. 1997).

To understand why perceiving and producing music are such powerful human experiences, it is necessary to consider how the perception of music develops. Musical structure consists of two basic aspects, a pitch aspect and a rhythmic aspect. The present chapter focuses on the development of musical pitch processing. It also focuses primarily on Western musical structure, because this is the only musical system for which there is substantial developmental data. The following sections examine behavioral and neural development for musical pitch processing and the effects of experience on development.

2 Musical Pitch Structure: Universal and System-Specific Aspects

Before considering the development of sensitivity to musical pitch in subsequent sections, here the various aspects of musical pitch structure are outlined. Which aspects are universal across musical systems and which aspects are specific to Western musical structure are also considered. A general prediction that can be made is that universal musical elements likely reflect aspects of auditory processing that capitalize on features of the auditory system; therefore, these elements could be fairly easy to learn and might develop relatively early. On the other hand, features that are specific to one musical system might reflect more mature ways of processing and, therefore, require more experience and develop later.

Musical pitch is complex and hierarchical in nature (Shepard 1964; Krumhansl 1990). At the most basic level, individual musical tones have a particular *pitch height,* ordered from low to high. This aspect of pitch processing is universal and domain general, applying, for example, to speech as well as music. A second level of the pitch hierarchy arises because tones with fundamental frequencies an octave apart, a doubling of frequency, are perceived as similar. Indeed, in Western musical notation, notes an octave apart are given the same note name (e.g., C, D, E) and are

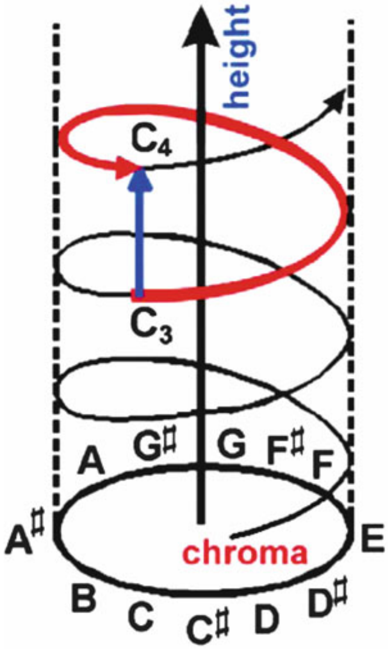


Fig. 8.1 Helical representation of pitch similarity. Pitch height is represented in the vertical dimension and chroma around the circle. The distance between two points represents their perceived similarity, accounting for both the similarity of adjacent tones and tones separated by octaves [Adapted from Shepard (1965). Reprinted by permission]

referred to as *chroma*. When listeners are asked to rate the similarity of pairs of tones, they take into account both pitch height and pitch chroma, and perceived similarity can be represented geometrically by a helix (Shepard 1982) (Fig. 8.1). Although the particular chroma used differ across musical systems, the height and chroma dimensions of musical pitch appear to be universal.

The perceptual similarity of notes an octave apart is undoubtedly related to another fundamental and universal aspect of pitch perception, that of the continuum between *consonance* and *dissonance*. Most simply defined, two notes played simultaneously are said to be consonant when they sound pleasant or smooth together whereas they are said to be dissonant when they sound rough or unpleasant. The octave is the most consonant musical interval. Consonance and dissonance contribute to people's emotional experiences of music because dissonance increases musical tension and consonance releases this tension.

Pitch is encoded in the nervous system via two mechanisms, a temporal code corresponding to the repetition rate or frequency of the incoming sound, and a spatial code whereby different frequencies are represented across neural tissue in an orderly fashion to produce tonotopic maps. Clear tonotopic maps are found in all auditory subcortical nuclei as well as in primary auditory cortex. Despite this absolute frequency organization, most people are rather poor at remembering the exact or *absolute pitch* of individual tones. On the other hand, people are generally quite good at remembering pitch intervals—the distance between two pitches—or *relative pitch*. For example, people recognize a familiar tune, such as "Happy Birthday",

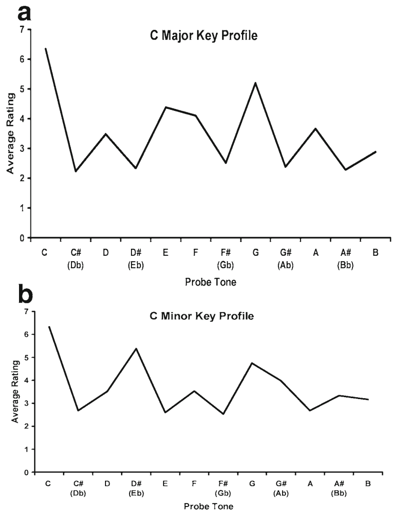
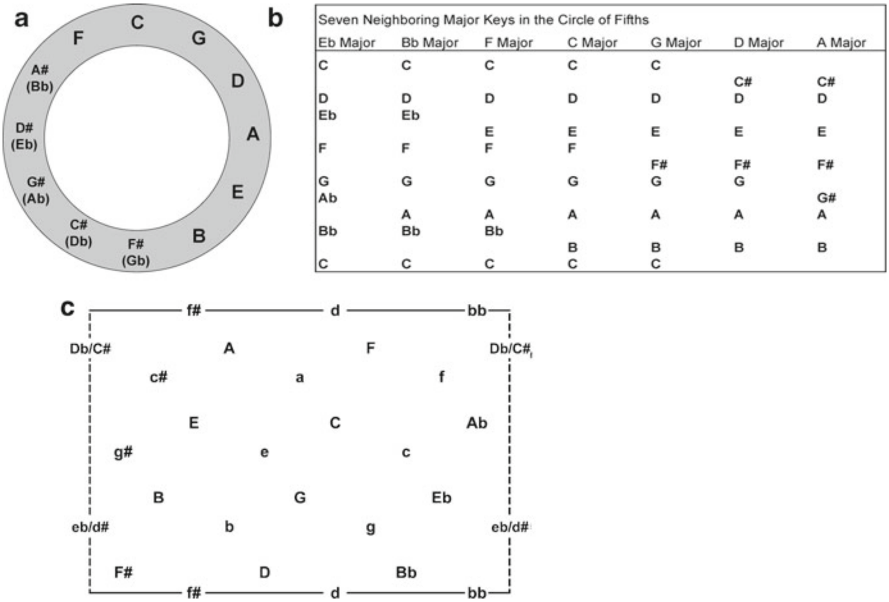


Fig. 8.2 Probe tone ratings for the keys of (**a**) C major and (**b**) C minor. Experienced musicians heard a key context (either a tonic triad or one of three chord cadences) and were then asked to rate how well a probe tone (taken from all 12 notes found within an octave in Western music) fit that context. For both major and minor contexts, tonic tones were always rated highest, followed by the other notes within the scale. Non-scale tones were always rated lowest [Adapted from Krumhansl and Kessler (1982) with permission of the American Psychological Association]

regardless of the absolute pitch of the starting note, as long as the intervals or pitch distances between the notes of the song are correct. This phenomenon, known as *transpositional invariance*, indicates that music is largely encoded in long-term memory in terms of relative rather than absolute pitch. The dominance of relative pitch encoding and transpositional invariance are likely universal across musical systems, although the prevalence of the use of absolute pitch encoding changes with culture and is likely influenced by experience (e.g., Deutsch et al. 2004).

One very interesting aspect of musical pitch structure is that music is generally not composed using continuous pitch but, rather, using a small number of *discrete pitch categories*, subdivisions of the octave. The collection of pitch categories forms a musical *scale*. The use of scales is near universal, but the particular scales used vary considerably from one musical system to another. In the most common Western scales, each note of the scale relates to the others in a unique way and takes on a specific function; the idea that different notes of the scale have different degrees of stability or importance is referred to as the *tonal hierarchy* (Fig. 8.2).

Because of transpositional invariance, a scale can begin on any note and it retains its identity as long as it contains the correct structure of pitch distances or intervals between notes of the scale. In Western music, 12 major scales can be created starting on each of the notes formed by subdividing the octave into 12 equal intervals (on a log scale) called semitones. Each one of these scales is called a musical *key*, and Western musical compositions are typically in one key at any particular time. Each of the 12 keys is most closely related to two other major keys with which it shares



Seven Neighboring Major Keys in the Circle of Fifths						
Eb Major	Bb Major	F Major	C Major	G Major	D Major	A Major
C	C	C	C	C		
					C#	C#
D	D	D	D	D	D	D
Eb	Eb					
		E	E	E	E	E
F	F	F	F			
				F#	F#	F#
G	G	G	G	G	G	
Ab						G#
	A	A	A	A	A	A
Bb	Bb	Bb				
			B	B	B	B
C	C	C	C	C		

Fig. 8.3 Representations of key relatedness. (**a**) Western major keys can be represented on a circle in which adjacent keys are most closely related. (**b**) Adjacent keys are separated by a perfect fifth and share all but one scale note. *C* major, for example, shares all scale notes except *F* natural with *G* major, and all but *B* natural with *F* major. (**c**) The rectangular map is a two-dimensional representation of the relatedness between all 24 Western major (*uppercase*) and minor (*lowercase*) keys. The *top* and *bottom* of the map are identical, as are the *left* and right edges, so this is a two-dimensional representation of a three-dimensional *torus* [Adapted from Krumhansl and Kessler (1982) with permission of the American Psychological Association]

6 of its 7 notes. The 12 keys can be arranged in a circle such that the farther away two keys are on the circle, the fewer notes they share and the less related they are (Fig. 8.3a, b). Transpositions from one key to another are most likely to occur between related keys. Western musical structure also includes a minor key associated with each major key. The major and natural minor keys contain the same notes, but the tonic is shifted down two notes in the minor relative to the major version. The major and minor keys can be represented in a map of tonal pitch space in which the distance between keys in the space corresponds to how closely they are related (Fig. 8.3c). Physiologically, the representation of musical keys appears to involve complex brain networks, including frontal brain regions (Janata et al. 2002).

In addition to the sequential pitch structure of melodies, Western music has prominent *harmonic structure*. Indeed, each note of a melody can be associated with a chord as when chord-based accompaniment is provided. Chords are typically built on the seven notes of the scale. Harmonic structure has a kind of loose syntax whereby certain chords are expected to follow other chords in sequence. Violations of harmonic expectations are frequently used in musical composition, and can give rise to emotional experiences in listeners (Meyer 1956; Huron 2006). Even musically untrained Western listeners are quite sensitive to harmonic expectations, showing smaller event-related potential (ERP) brain responses to expected chords compared to unexpected chords (Koelsch et al. 2000).

In summary, although musical pitch is based on domain-general mechanisms for pitch processing, there are many layers of pitch structure in music. Some of these layers are very common across musical systems, such as the dimensions of pitch height and chroma, consonance and dissonance, transpositional invariance, the use of discrete pitch categories, scales with different sizes of intervals, and tonal pitch spaces. However, different musical systems use different musical scales and tonal pitch spaces, and the use of complex harmony appears to be largely limited to Western musical structure. In the next section the development of these aspects of musical pitch is explored.

3 Development of Musical Pitch Processing

3.1 Basic Pitch Perception

Sounds with energy at only one frequency are referred to as pure or sine tones. However, sounds with pitch are typically complex in that they have energy at a fundamental frequency, corresponding to the perceived pitch, and at harmonics at integer multiples of that frequency. Normally, the frequency components are fused into a single percept. All components contribute to the perceived pitch, as the pitch does not change when the fundamental frequency is removed.

As outlined by Buss, Hall, and Grose (Chap. 4), young infants are able to discriminate tones of different frequencies although their performance is poorer than that of adults. However, discrimination is good enough to support the perception of musical pitch. A related question concerns whether infants and adults use similar cortical mechanisms for discriminating tones. This question can be addressed by measuring event-related potentials (ERPs) derived from electroencephalogram (EEG) recordings. The general immaturity of auditory cortex in young infants is seen in that the frequency of the dominant oscillatory rhythm from auditory regions increases from 4 to 5 Hz at 4 months to 6–7 Hz at 12 months to around 10 Hz in adults (Fujioka et al. 2011). In adults, presentation of a tone triggers a series of responses over a few hundred milliseconds (ms) that represent the stages of sound processing (Fig. 8.4), beginning with auditory brainstem responses (within the first 15 ms after sound onset), followed by middle latency responses from primary auditory cortex (<50 ms after sound onset), followed by sensory, perceptual and cognitive cortical responses, including P1 (the first large frontally positive response ~50 ms), N1 (the first large frontally negative response ~100 ms), P2 (~170 ms), N2 (depending on attention, ~250 ms) and P3 (relating to conscious performance of a task, at various latencies depending on the task). Activity in auditory cortex generally gives rise to a dipolar pattern on the surface of the head, with a negativity at

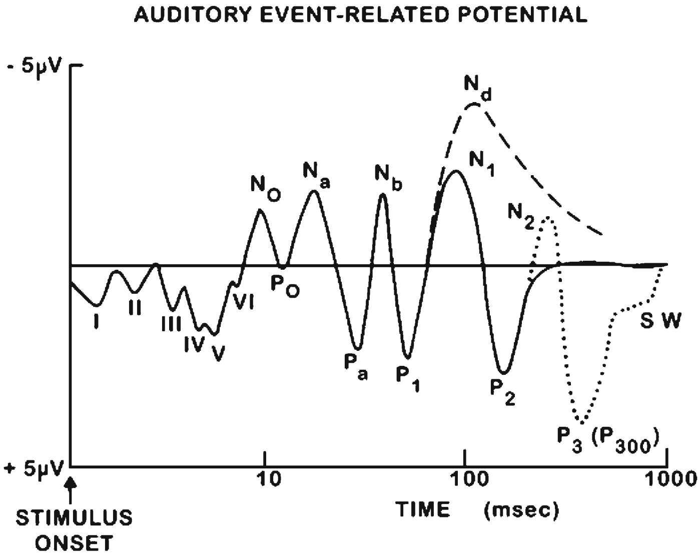


Fig. 8.4 Stylized representation of the auditory event-related potential (*ERP*) from a frontal site on the surface of the head. The auditory *ERP* shows the stages of processing in the brain's response to a sound and is derived from electroencephalogram (*EEG*) recordings. The first few peaks (I–VI) represent auditory brain stem responses; peaks N0, P0, Na, Pz, Nb, and P1 represent the middle latency responses from primary auditory cortex; N1 and P2 represent processing from secondary auditory areas. N2, Nd, and P3 are nonobligatory responses reflecting attention, memory and decision processes [From Trainor (2008b). Reprinted with permission of Cambridge University Press]

frontal sites accompanied by a positivity at posterior sites, or vice versa. Interestingly, these components take a very long time to mature. Specifically, the N1 and P2 components are so small as to be difficult to measure before about 4 years of age. They decrease in latency and increase in amplitude until about 10–12 years of age, and decrease thereafter, reaching stable adult levels in the late teenage years (Ponton et al. 2000; Shahin et al. 2004) (Fig. 8.5a). This protracted development suggests that these components represent feedback connections from other brain regions that provide top-down signals to auditory cortex. After early hearing deprivation, these components do not develop normally (Eggermont and Moore, Chap. 2).

Despite the late emergence and slow maturation of the obligatory responses to sound described in the previous paragraph, ERP components reflecting the brain's response to occasional changes in an ongoing stream of sound emerge much earlier (Trainor 2008b). Indeed, the main task of the perceptual system can be seen to be one of predicting the future based on the past, and performing extra processing to update representations of the state of the world when a prediction is incorrect (Huron 2006; Trainor and Zatorre 2009). In adults, virtually any occasional detectable change (e.g., in pitch, intensity, timbre, pattern) in an ongoing sequence of sounds gives rise to an additional negativity, termed a mismatch negativity (MMN), peaking at frontal sites on the scalp between 120 and 250 ms after stimulus onset depending on the complexity

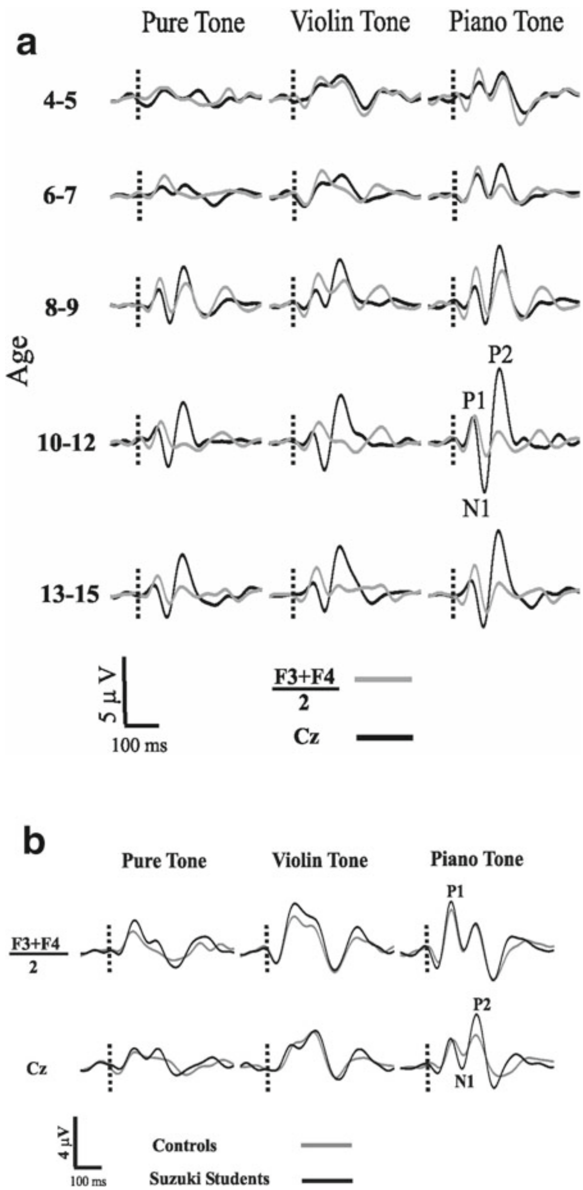


Fig. 8.5 Development of auditory event-related potential (ERP) components. (**a**) The protracted development of the N1 and P2 ERP components is shown in response to pure tones, violin tones and piano tones. The *dotted lines* represent sound onset. Components increase in amplitude up to 10–12 years of age, and then gradually decrease to stable adult levels over the teenage years. (**b**) 4- and 5-year-old children engaged in musical training show enhanced N1 and P2 responses compared to control participants not training musically. F3 and F4 are *left* and *right* frontal scalp regions, respectively, and Cz is a central scalp region [From Shahin et al. (2004). Adapted with permission of Wolters Kluwer/Lippincott, Williams & Wilkins]

of the change. The ERP responses of young infants to single tones are dominated by frontally positive slow waves, components that disappear with increasing age. At 2 months of age, occasional changes in pitch primarily elicit an increase in the amplitude of this frontally positive slow wave (He et al. 2007, 2009). However, by 3 months an MMN with adult-like morphology is evident, which decreases in latency and increases in amplitude with increasing age (Fig. 8.6). Thus, young infants are

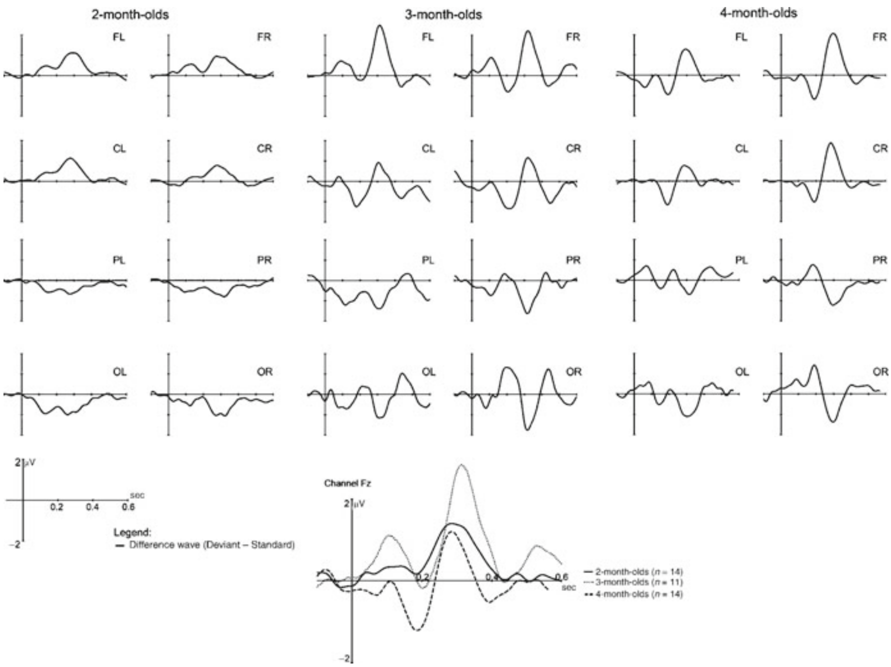


Fig. 8.6 Event-related potential (ERP) responses in early infancy to occasional pitch changes. On standard trials (80%) a C5 piano tone (523 Hz) was presented and on deviant trials (20%) an F#5 piano tone (740 Hz) was presented. Shown are the ERP difference (deviant-standard) waves at left (*L*) and right (*R*), frontal (*F*), central (*C*), parietal (*P*), and occipital (*O*) scalp regions. The *y*-axis represents tone onset. The ERPs reverse in polarity from front to back of the head, consistent with a neural generator in auditory cortex, which is located between these sites. In response to the change in pitch, 2-month-olds show only an increase in a frontally positive slow wave, whereas 3- and 4-month-olds show a faster, frontally negative wave much like the adult mismatch negativity (MMN), followed by a positivity much like the adult P3a. [From He et al. (2007). Reprinted with permission of MIT Press]

able to discriminate tones with different fundamental frequencies, but an adult-like cortical mechanism for this takes a few months to emerge.

When processing complex tones, the auditory system breaks incoming sounds into their frequency components, and much subcortical processing takes place within frequency-specific channels. Such analysis of the frequency content of sounds is crucial for separating simultaneous sound sources with overlapping frequency content and for the perception of timbre (Leibold, Chap. 5). Evidence from monkeys suggests that the harmonics of a complex tone are not integrated into a single pitch representation subcortically or in primary auditory cortex (Fishman et al. 1998), but that pitch is first extracted in a region adjacent to primary auditory cortex (Bendor and Wang 2005). Studies in humans examining functional magnetic resonance imaging (fMRI) responses (Patterson et al. 2002; Penagos et al. 2004) and effects of lesions (Schönwiesner and Zatorre 2008) indicate a similar organization.

Given the immaturity of auditory cortex during the first months after birth, it might be expected that very young infants can discriminate pure tones, but cannot initially integrate harmonics into a single pitch percept. Complex pitch perception can be studied with stimuli in which the fundamental frequency has been removed, because if the fundamental is present, there is no way of determining whether the subject is integrating all of the harmonics into a pitch percept or attending only to the fundamental frequency. If removal of the fundamental does not change the perception of the pitch, then it is clear that the subject must have integrated the harmonics in order to perceive the pitch. Clarkson and Clifton (1985) presented 7-month-old infants with different tones containing various harmonics but all missing the fundamental. They used a *conditioned head turn procedure* in which the set of missing-fundamental tones was presented in random order from a loudspeaker to the side of each infant. Occasionally a tone with a different pitch was presented, and if infants turned their heads at least 45° toward the sound source when this occurred, they were rewarded with dancing toys for a couple of seconds. Head turns at other times were not rewarded, and discrimination was determined by comparing the proportion of head turns when there was a change in pitch to when there was not. Clarkson and Clifton found that the infants were able to ignore the timbre changes and respond to changes in the pitch of the missing fundamental. At the same time, the infants, unlike adults, were unable to do the task if only high harmonics were present (Clarkson and Rogers 1995), indicating that basic pitch perception is not yet adult-like at 7 months.

He and Trainor (2009) used ERPs to investigate the emergence of pitch perception. They presented standard tone pairs in which the fundamental and different harmonics were present on each trial. In each standard tone pair, the frequency of all harmonics, as well as the overall pitch, increased from the first to the second tone, although the pitch of the first tone and the increase in frequency varied from pair to pair. Occasionally He and Trainor presented a deviant tone pair in which the frequency components of the second tone lined up to produce the pitch of a missing fundamental frequency that was lower than the pitch of the first tone (Fig. 8.7a). Note that in deviant tone pairs the frequency of each component increased from the first to the second tone just as in the standard stimuli, so that if the pitch of the missing fundamental was not perceived, deviant stimuli would generate similar ERP responses as standard stimuli. He and Trainor found that adults, 7-month-olds and 4-month-olds responded to the pitch reversal in the deviant pairs, but found no evidence that 3-month-olds did (Fig. 8.7b). Thus it appears that the ability to integrate harmonics into a pitch percept emerges between 3 and 4 months of age.

In sum, although frequency discrimination is good enough in early infancy to support musical pitch processing, auditory cortex remains immature for a protracted period. ERP components related to communication between auditory areas and other brain regions do not mature until the late teenage years. The ability to integrate the harmonics of a complex tone into a unified pitch representation relies on brain regions beyond primary auditory cortex and may not emerge until several months after birth.

3.2 Consonance and Dissonance

The consonance/dissonance continuum is one of the fundamental organizing principles of musical pitch. In adults, increases and decreases in consonance and dissonance give rise to increases and decreases in perceived tension, which in turn give rise to the ebb and flow of perceived emotion in music (Smith and Cuddy 2003). One explanation of the perceptual difference between consonance and dissonance involves the structure of the inner ear. Tones whose fundamental frequencies stand in simple integer ratios, such as the octave or perfect eighth (2:1 ratio) or the perfect fifth (3:2 ratio), tend to sound consonant whereas tones whose fundamental frequencies stand in more complex integer ratios, such as the major seventh (15:8) or tritone (45:32), tend to sound dissonant. Most of the lower, most salient harmonics of consonant tone pairs are either the same or are separated by more than a critical bandwidth (about one-fourth of an octave for much of the frequency range). In contrast, highly dissonant tone pairs have many harmonics between them that are less than a critical bandwidth apart. When two frequency components across simultaneous complex tones (whether fundamentals or harmonics)

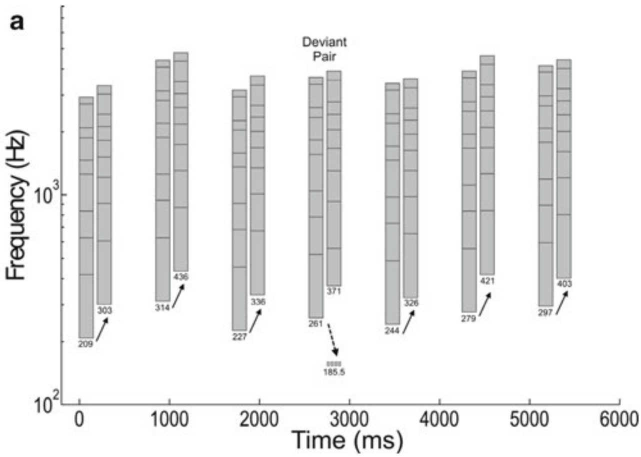


Fig. 8.7 Processing the missing fundamental in infancy. (**a**) The stimuli were complex tones (*gray bars*) created using 10 harmonics (*black lines* within the *gray bars*) from the first 15 harmonics. All trials consisted of a tone pair in which every harmonic increased from the first to the second tone of the pair. For standard pairs (80%), the pitch corresponded to the lowest harmonic (fundamental), and the pitch increased from the first to the second tone. However, in the case of deviant pairs (20%) the harmonics of the second tone in the pair were all integer multiples of a missing fundamental that was lower than the frequency of the lowest harmonic in the first tone. Therefore, if the pitch of the missing fundamental was perceived, the pitch rose from the first to the second tone in the standard pairs, but the pitch fell in the case of deviant pairs. However, if the harmonics were not integrated into a pitch percept, standard and deviant pairs would not be distinguishable as all individual harmonics rose from the first to the second tone for both trial types.

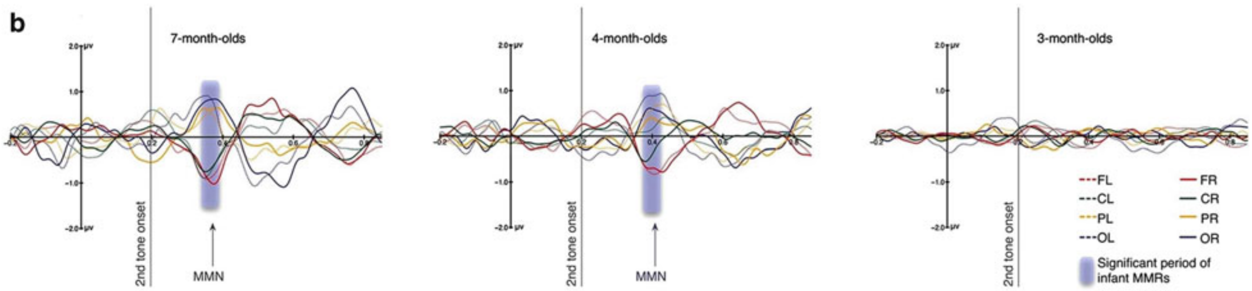


Fig. 8.7 (continued) (**b**) Event-related potential (ERP) difference waves (deviant – standard trials) at left (*L*) and right (*R*), frontal (*F*), central (*C*), parietal (*P*), and occipital (*O*) scalp regions. The mismatch negativity (MMN) component (highlighted by the *gray bars*) can be seen at 7 and 4 months of age by the frontal negativity simultaneous with a posterior positivity in the difference waves. Thus, 7-month-old and 4-month-old infants, but not 3-month-old infants, showed evidence of cortical response to the pitch of the missing fundamental [From He and Trainor (2009). Reprinted with permission of the Society for Neuroscience]

are less than a critical bandwidth apart they cannot be represented independently on the basilar membrane in the inner ear, and the complex patterns of activity they elicit give rise to the sensation of beating or roughness. It has been proposed that it is the roughness and beating of such stimuli that give rise to the sensation of dissonance (Plomp and Levelt 1965).

There is also evidence that the consonance/dissonance distinction arises from the distinct temporal firing patterns that consonant vs. dissonant intervals set up in the auditory nerve fibres (Tramo et al. 2001). Indeed a recent study suggests that it is the harmonicity (i.e., whether harmonics stand at integer multiples of a fundamental) rather than roughness that plays the greatest role in determining perception of consonance versus dissonance (McDermott et al. 2010). Regardless of whether the perception of consonance and dissonance is the result of complex vibration patterns on the basilar membrane or temporal firing patterns in the auditory nerve, its origin is relatively peripheral in the nervous system in both cases. Consistent with this, the perception of consonance and dissonance appears to be quite similar across cultures for isolated tones, although effects of the surrounding musical context on consonance perception may differ substantially across cultures.

If the distinction between consonance and dissonance is peripheral in origin, sensitivity might be expected to emerge early in development. Indeed, infants, like adults, are better able to process consonant than dissonant intervals. When highly consonant intervals, each consisting of two simultaneous tones, are presented in random order, infants readily detect when a dissonant tone is inserted, but they are not able to detect a consonant interval inserted into a set of dissonant intervals (Trainor 1997). Infants are also better at detecting a semitone change from a perfect fifth interval that creates a dissonant interval compared to a larger whole tone change that creates another consonant interval (Schellenberg and Trainor 1996). Finally, in melodic contexts, infants can more easily detect changes in melodies with prominent consonant intervals compared to melodies with prominent dissonant intervals (Trainor and Trehub 1993). Together, these studies indicate that the consonance/dissonance continuum is perceptually salient to infants and has consequences for the processing of tonal information.

It is also of interest that in addition to a processing advantage for consonance, infants prefer consonance over dissonance. Using looking time preference procedures in which infants determine how long they listen to the sound presented on each trial by how long they look at a visual display—the sound for each trial ends when the infants look away from the visual display—it has been revealed that infants as young as 2 months prefer to listen to consonant over dissonant intervals in isolated contexts or in the context of simple musical pieces (Trainor and Heinmiller 1998; Zentner and Kagan 1998; Trainor et al. 2002b). Indeed, this preference is found very early and without prenatal speech exposure in hearing newborns of deaf parents (Masataka 2006).

The origin of the preference for consonance over dissonance is not known. It could possibly be innate, or it could arise from experience with the harmonics of complex tones, in which the lower, most salient harmonics form consonant intervals (Terhardt 1974). It might also be related to ease of processing. Simultaneous tones that form dissonant intervals have harmonics that are close in pitch but not identical.

Such harmonics are processed within a critical band and therefore are not represented completely independently on the basilar membrane making it difficult to determine the exact frequencies present. Whatever the case, it is clear that sensitivity to the consonance/dissonance continuum arises very early in development.

Much of musical pitch structure relates back to the consonance/dissonance continuum. *Octave equivalence*, that tones an octave apart sound similar, is a near-universal feature of musical systems (Burns 1999) and likely arises because tones an octave apart share most of their harmonics, and because the octave is the most consonant interval. When people sing together and their voices are in different pitch ranges, they normally sing octaves apart. Like consonance and dissonance, infants are sensitive to octave relationships (Demany and Armand 1984). Octave equivalence, in turn, enables the emergence of musical scales, which divide the octave into discrete intervals. Musical scale intervals are also influenced by the consonance/dissonance continuum as the more prominent intervals in musical scales are also the most consonant (e.g., the interval between the two most stable notes of the Western major scale is a perfect fifth or 3:2 ratio).

In sum, sensitivity to consonance and dissonance emerges early, as does a preference for consonance. Because of its relation to octave equivalence and musical scale structures, it is possible that the consonance/dissonance continuum is the fundamental organizing principle for musical pitch structures.

3.3 Transpositional Invariance

Transpositional invariance is not specific to musical pitch structure in that people readily recognize, for example, speech sounds, whether spoken in a high or low pitch range. But transpositional invariance is crucial for musical pitch structure, first, because it enables recognition of melodies across a wide variety of contexts and, second, because melodies often contain short pitch patterns that are repeated at different pitch levels, which give melodies a sense of cohesion. Transpositional invariance requires ignoring the absolute pitch information and attending to the relative pitch distances between tones. Interestingly, young infants have transpositional invariance in that they treat melodies transposed to different starting notes as similar, readily detecting occasional differences in relative pitch structure despite the fact that the transposed versions being compared have no actual notes in common, only relative pitch distances (e.g., Trehub et al. 1984; Trainor and Trehub 1992; Chang and Trehub 1977). Not only can adults recognize melodies in transposition, but it is the normal mode of processing for most adults. There is evidence that infants (Saffran and Griepentrog 2001; Volkova et al. 2006) and adults (Schellenberg and Trehub 2003) can remember absolute pitch under some circumstances, but for both age groups, relative pitch and transpositional invariance appear to be the normal mode of processing. Although access to absolute pitch is maintained in working memory, for most people, absolute pitch information fades rapidly. Given a target tone to remember, the presentation of interference tones with random pitch dramatically reduces most adults' ability to identify the pitch of the target tone (Ross et al. 2004). Similarly, infants' ability to compare the pitch of two tones decreases with an increasing number of random pitch interference tones (Plantinga and Trainor 2008).

Infants' long-term memory representations for melodic pitch are also primarily in terms of relative pitch. Plantinga and Trainor (2005) tested this by playing a few repetitions of a melody daily for infants over the course of a week and then examining their listening preferences. Half of the infants were familiarized with one melody whereas the other half heard a second melody. After a 1-day delay between last familiarization and testing, infants looked longer on trials presenting the unfamiliar melody compared to the familiar melody, indicating that they remembered the melodies. Of most interest here, in a second condition, both melodies were transposed up or down by either a perfect fifth or a tritone. Under transposition, every note of each melody is different, making recognition dependent on a relative pitch representation. Preferences for the novel melody under transposition were as strong as when familiarization and test melodies were at the familiarized pitch, indicating robust relative pitch representations. Furthermore, when the familiar melody was presented in two versions during the preference test, one at the pitch heard during familiarization and one transposed, infants showed no preference, again indicating that either they do not have a long-term representation for the absolute pitch or it is not salient to them.

ERP data reveal that transpositionally invariant representations of melodies can be found in auditory cortex at 6 months of age. When a four-note melody was presented in transposition, occasional wrong notes in the final position elicited brain responses, indicating that infants detected the changes (Tew et al. 2009). Interestingly, although occasional changes in the pitch of a single repeated tone elicited MMN responses with an adult-like morphology by 3 months of age as discussed above, for melodies, the mismatch response remained immature even at 6 months. Specifically, instead of a frontally negative/posteriorly positive response to the deviant tones as seen in adults, when the melodic/transpositional context required relative pitch processing, 6-month-olds showed an increase in the frontally-positive slow wave in response to the deviant tones. This response is similar to that shown by younger infants in response to simple pitch changes (see Sect. 3.1). Thus, although infants process relative pitch early in development, the cortical mechanisms and sound representations remain immature for some time. It is not yet known when they mature.

In sum, as early as has been tested, infants show robust processing of relative pitch in both short-term and long-term memory representations. This ability is domain-general to an extent, being important for detecting invariance in speech and various environmental sounds. Its early emergence is likely an important prerequisite for musical acquisition.

3.4 Learning Musical Scales and the Tonal Hierarchy

Music is composed from sets of discrete notes or scales. The most common scale in Western music is the major scale. It contains two interval sizes between adjacent notes of the scale, the tone (1/6th of an octave) and the semitone (1/12th of an octave), such that it divides the octave into an ordered set of seven intervals: tone, tone, semitone, tone, tone, tone, semitone. Although the use of scales is near universal, the particular scales used vary across musical systems. Therefore, it is necessary to learn the particular musical scales of one's culture, just as it is necessary to learn the language of one's culture. And just as children learn the language of their culture through exposure but no formal training, children acquire implicit knowledge about the scale structure of their culture through mere exposure. Adults without formal musical training and no explicit knowledge of musical nomenclature and structure have considerable implicit knowledge about the musical system to which they have been exposed (e.g., Trainor and Trehub 1994; Bigand and Poulin-Charronnat 2006; Bischoff Renninger et al. 2006; Tillmann et al. 2006).

By at least as young as 2 months of age, infants can discriminate unfamiliar melodies (Plantinga and Trainor 2009) and by 6 months infants can remember melodies for weeks (Saffran et al. 2000; Trainor et al. 2004; Ilari and Polka 2006). On the other hand, it takes infants exposed to Western music some time to learn key membership, or which notes belong in a key. Trainor and Trehub (1992) presented adults and 8-month-old infants with a ten-note melody and measured their ability to detect occasional note changes. Adults were much better at detecting changes to notes that did not belong to the key of the melody in comparison to changed notes that remained within the key. On the other hand, infants were equally good at detecting both change types, indicating that they had not yet acquired knowledge of key membership for the Western major scale. Lynch et al. (1990) examined cross-cultural processing. They found that Western adults were much better at detecting changed notes in melodies based on the Western major scale compared to melodies based on an unfamiliar Balanese scale. Infants, on the other hand, performed equally well with melodies in the two scales. The exact age at which children acquire musical system-specific knowledge remains unknown, and likely depends on the amount and type of music experience they have. Lynch and Eilers (1991) found that 10–13-year-old children were better able to detect changes to the Western major than to the Javanese pelog scale, but this sensitivity likely emerges much earlier in development. Studies examining the ease of detection of within-key compared to out-of-key notes in Western melodies indicate that by 4 or 5 years of age, key membership for Western music is in place (Trehub et al. 1986; Trainor 2005; Corrigall and Trainor 2009).

Although musical scales do differ across musical systems, some structural properties are near universal, just as some properties of languages are near universal (Chomsky 1965). One common feature of musical scales is that they contain intervals of more than one size. These asymmetries of the interval structure are vital to musical pitch organization as they enable different notes of the scale to take on different functions. For example, in the Western major scale, every note forms a unique set of intervals or pitch relations with the other notes of the scale (Balzano 1980) so each takes on a different identity. Interestingly, even infants are better able to process unfamiliar scales with more than one interval size compared to unfamiliar scales with equal intervals (Trehub et al. 1999).

Asymmetrical interval structure enables scales to have *internal* structure as well, in the form of the tonal hierarchy. Different notes of the scale have different musical meanings. The first note of the Western major scale, the tonic, is the most stable and compositions typically begin and end on the tonic. The second degree, or supertonic, sounds resolved if it falls to the tonic. Similarly, the last (seventh) scale degree, or leading tone, sounds resolved if it rises to the tonic. The fifth degree, or dominant, is the second most stable note of the scale and it bears a consonant relation (3:2 frequency ratio) to the tonic. The fourth degree, or subdominant, is the next most stable note, and also bears a consonant relation (4:3 frequency ratio) to the tonic. Together with the tonic and dominant, the third degree or mediant forms a tonic triad, a common melodic pattern. To examine the psychological reality of the tonal hierarchy Krumhansl developed the probe tone method, whereby a musical context such as a scale is presented, followed by a single probe tone, and participants rate how well the probe tone fits the context (Krumhansl 1990). Krumhansl found a consistent profile of ratings for the different notes of the Western scales (see Fig. 8.2) showing that Western adults are sensitive to musical key structure (Krumhansl and Cuddy 2010). Even adults without formal musical training are sensitive to these semantic relations (Trainor and Trehub 1994; Koelsch et al. 2002a, 2003a; Bigand and Poulin-Charronnat 2006). Using a similar probe-tone methodology, it has been shown that from first grade, children rate in-key notes as fitting better into the key context than out-of-key notes, but that sensitivity to the full tonal hierarchy does not emerge until later into the school-age years (Krumhansl and Keil 1982; Speer and Meeks 1985; Cuddy and Badertscher 1987).

Thus, young infants can remember melodies and are sensitive to universal aspects of scale structure such as unequal interval sizes. At the same time, it takes considerable experience for sensitivity to culture-specific scales to arise. Developmentally, sensitivity to key membership, or knowing which notes belong in a key and which do not, arises earlier than sensitivity to the tonal hierarchy, or understanding the different meanings of different notes within a key.

3.5 Learning Harmonic Syntax

Although particular musical scales differ across musical systems, the use of scales that divide the octave into a small number of discrete intervals is widespread. In contrast, the elaborate harmonic structure of Western music is fairly unique. In this regard, it is interesting that the implicit acquisition of harmonic rules is relatively late developing, likely not reaching adult levels until the early teenage years (Costa-Giomi 2003). Knowledge of harmonic structure depends on an underlying perception of consonance and dissonance. The structurally most important chords in a major key are based on the tonic (I chord), dominant (V chord), and subdominant (IV chord). (Roman numerals refer to the scale position of the note the chord is based on.) These are major chords, with the higher notes forming a major third (ratio of 5:4), perfect fifth (3:2) and octave (2:1) interval with the root or scale note of the chord. Chords built on the supertonic (ii chord), mediant (iii chord), and submediant (vi chord) are next most consonant, with the higher notes forming a minor third (6:5), perfect fifth (3:2) and octave (2:1) with the root or scale note of the chord. The chord built on the leading tone is more dissonant, with the higher notes forming a minor third (6:5), diminished fifth (45:32) and octave (2:1) with the root of the chord. The sequential ordering of chords in composition follows probabilistic syntactic rules, such that certain chord progressions are much more likely than others. For example, V and vii° chords create tension, which is resolved when they are followed by a I chord. Tension and tone color can be enhanced with the addition of other notes to the chord, most commonly by the addition of a note that forms a seventh interval with the root of the chord. For example, when the minor seventh (16:9) interval is added to a dominant chord, it increases the dissonance and therefore the experienced tension, which in turn increases the sense of resolution when it is followed by a I chord. A diminished seventh is often added to a vii° chord, again to increase dissonance, tension, and degree of resolution.

Although an adult level of harmonic understanding is not achieved until much later, the beginnings of understanding syntax for chord progressions can be seen in preschool and school-age children. In an implicit task, Schellenberg et al. (2005) showed that children as young as 6 years of age were faster to identify features of the last chord of a sequence, such as its instrument timbre or sung phoneme, when it was an expected tonic (I) chord compared to when it was an unexpected subdominant (IV) chord. Using a child-friendly task involving puppets, Corrigall and Trainor (2009) showed that children as young as 4 years of age rated sequences as sounding "good" more often when they ended on an expected tonic chord compared to when they ended on an unexpected subdominant chord. Similar results have also been obtained with ERP measures. Children as young as 5 years of age showed different EEG responses when presented with a highly unexpected chord at the end a sequence of chords compared to an expected chord (Koelsch et al. 2003b).

Harmonic structure is so pervasive in Western music that even melodies presented in isolation set up expectations for an underlying harmonic chord–based accompaniment. The psychological reality of these implied harmonic expectations are apparent in adults' detection of wrong notes in a melody. Trainor and Trehub (1994) showed that adults are better able to detect a wrong note in a melody that remains within the key of the melody when the wrong note violates the implied harmony expected at that point, compared to when it is consistent with that harmony. They found that 7-year-olds but not 5-year-olds were adult-like in this ability.

In sum, harmony is relatively rare across musical systems and sensitivity to harmonic structure develops relatively late. Although some sensitivity can be seen in preschool children, it continues to develop well into middle childhood.

3.6 Summary of Research on the Development of Musical Pitch Processing

Musical pitch structure is multifaceted. Certain basic aspects of pitch structure, such as pitch discrimination, consonance and dissonance, and transpositional invariance are processed very early in development. These abilities form the basis for the development of higher-level pitch structures. Most important of these in Western music are scales (keys) and harmony (chord sequences). The use of scales as the basis of melodic composition is essentially universal across musical systems, and scales share certain properties such as octave equivalence, the use of a small number of notes or scale degrees per octave, and more than one size of interval between scale notes. These universal features of scales can all be processed in infancy. At the same time, the particular scales used vary considerably between musical systems and are learned through exposure some time after 8 months of age. Harmonic syntax, on the other hand, is relatively rare across musical systems and shows a protracted developmental trajectory. Sensitivity to some aspects of harmony appears by 4 years of age, but full sensitivity is probably not achieved until the teenage years.

4 Effects of Experience on Musical Pitch Processing

The general finding that development is greatly influenced by experience applies to musical acquisition (Trainor and Corrigall 2010). Just as young children learn to speak the language of their culture without formal training, they learn the pitch structure of their musical system as well, although adults without formal musical training typically do not have explicit knowledge of this structure. However, when implicit tasks are used, nonmusicians demonstrate quite sophisticated musical knowledge of key membership and harmonic syntax. In such tasks, participants are, for example, asked to make a judgment about whether the last chord of a sequence is in tune (Bharucha and Stoeckig 1986, 1987) or consonant (Bigand and Pineau 1997; Tillmann et al. 1998; Bigand et al. 1999). However, the manipulation of interest is whether or not the last chord is syntactically expected or not. Both musicians and nonmusicians are slower to make the above judgments when the chord is unexpected, indicating their knowledge of harmonic syntax. In the case of melodic processing, ERP studies indicate that even when melodic sequences are not attended to, the auditory cortex of nonmusicians responds to violations of expected pitch contour (up/down pattern of pitch changes) and expected melodic pitch interval (Trainor et al. 2002a).

Although nonmusicians develop networks in the brain that are specialized for processing the musical pitch structure they hear in their environment, there are vast differences between musicians and nonmusicians in the amount and type of musical experience they gain during development. Unlike language, where most people attend school and learn to read, typically musicians, but not nonmusicians, produce music, learn to read music and gain explicit knowledge about musical structure. In principle, these large differences in experience would be expected to affect brain development. Indeed, the brains of musicians and nonmusicians differ in many ways, as discussed later. However, in practice it is difficult to determine whether the differences seen in adulthood between musicians and nonmusicians are the result of differences in musical experience or whether they are largely due to genetic differences affecting early music processing and therefore the decision to train musically. The gold standard in this respect would be longitudinal studies with random assignment to groups receiving different musical experiences. In practice, this is difficult to achieve, and there are few studies that meet this standard. Therefore, most of the evidence for effects of formal musical experience on development is suggestive rather than definitive.

4.1 Structural Brain Differences Between Musicians and Nonmusicians

Music recruits a wide range of cortical areas (e.g., Koelsch and Siebel 2005; Schlaug 2009). Two regions that appear to be particularly important for musical pitch are the superior temporal and inferior frontal areas. These areas and the white matter tracts connecting them are compromised in individuals with poor music pitch processing (Hyde et al. 2006, 2007; Loui et al. 2009). Interestingly, the network connecting these regions is critical for language as well as for music, and it is likely involved in the processing of patterns of sounds.

Differences between adult musicians and nonmusicians have been reported for a number of cortical regions using MRI measures. Musicians show increased gray matter in Broca's Area (Sluming et al. 2002), the cerebellum (Hutchinson et al. 2003), and motor areas (Gaser and Schlaug 2003; Bangert and Schlaug 2006). Further, the degree of volume increase in auditory cortex correlates with behavioral musical skill (Schneider et al. 2002). The thickness of cortex has also been reported to be greater in musicians compared to nonmusicians, particularly in the right secondary auditory cortex and dorsolateral prefrontal cortex (Bermudez et al. 2009).

Simply knowing that these differences between adult musicians and nonmusicians exist does not clarify the extent to which they are the result of genetic differences or of formal musical training and many hours of practice. There has only been one MRI study to compare young children taking music lessons with children not taking lessons (Hyde et al. 2009). Children were tested at 6 years of age and again 15 months later. There was no random assignment to groups, but half of the children took music lessons of some kind outside of school whereas the other half did not. Initially there were no differences between the groups. However, after the 15 months, the musician children showed larger volume in certain motor areas as well as in the right primary auditory cortex. Changes in the latter were correlated with changes in behavioral performance on melodic and rhythmic discrimination. In sum, this one study is consistent with musical experience causing structural changes in the brain that would enhance pitch processing. It remains unknown as to whether there is a critical period during which such experience would have the greatest effect (Trainor 2005).

4.2 Effects of Experience on Processing Single Tones

Unlike fMRI, which has temporal resolution on the order of seconds, electroencephalography (EEG) and magnetoencephalography (MEG) recordings can measure the stages of processing in the brain with a submilliscecond resolution (Fig. 8.4), and thus can provide detailed information about the processing of individual tones in the brain. Differences between adult musicians and nonmusicians have been found at virtually every stage of processing. At the subcortical level, musicians show larger and temporally less variable responses to sounds compared to nonmusicians (Musacchia et al. 2007; Kraus and Chandrasekaran 2010). They also show increased steady-state responses originating in primary auditory cortex (Schneider et al. 2002). Automatic preattentive responses N1b (e.g., Pantev et al. 1998), N1c, and P2 (e.g., Shahin et al. 2003), originating in secondary auditory cortices, are also larger in musicians. Later components are larger as well, including P3a responses reflecting inadvertent capture of attention and bringing of sounds into consciousness (Fujioka et al. 2004, 2005) and P3b, reflecting memory and conscious processing of sound (e.g., Besson and Faïta 1995; Trainor et al. 1999; Tervaniemi et al. 2005). It is difficult to prove that these differences are the result of experience, but several lines of research suggest that experience plays a large role. First, the size of the N1b (Pantev et al. 1998) and P3b (Trainor et al. 1999) responses are correlated with the age of onset of music lessons. Further, the increase in N1b appears to be specific to the timbre of the instrument of practice. Specifically, violinists show a larger increase in N1 for violin tones whereas trumpet players show a larger increase for trumpet tones (Pantev et al. 2001). Second, laboratory training studies show that the P2 response is particularly neuroplastic. Increases in P2 responses were seen after training on frequency discrimination only for tones at the frequency trained (Bosnyak et al. 2004). In addition, MMN amplitude increases after controlled laboratory training in learning to play melodies on a keyboard (Lappe et al. 2008).

There is little work on the effects of musical experience on the processing of isolated tones. However, Shahin and colleagues (2004) reported that N1 and P2 in response to single tones were larger in 4- to 5-year-old children engaged in Suzuki music lessons compared to children not training musically (Fig. 8.5b). Fujioka et al. (2006) measured MEG responses to musical tones and noises in similar-age children beginning music lessons, and in children engaging in other extracurricular activities, every 3 months for a year. The largest difference in how the two groups changed over the course of the year was in the N2 component to music sounds, but not to noises, which likely reflects increased automatic attention for musical tones with musical training.

Although the literature on the processing of isolated tones focuses on the various slow components described earlier, oscillatory activity reflecting the activation of networks of neurons can also be studied by analyzing EEG and MEG signals in the frequency domain. Induced activity in the gamma band range (30–100 Hz) is of interest as it is thought to reflect the operation of attention and memory and the interaction of top-down and bottom-up processes (e.g., Bertrand and Tallon-Baudry 2000). Induced gamma band activity occurs in response to a sound, but it is not precisely phase-locked to the sound stimulus. It is therefore thought to reflect the recruitment of ongoing oscillatory activity in the brain for the processing of the sound. Induced gamma band activity in response to musical tones has been shown to be larger in adult musicians than in nonmusicians (Shahin et al. 2008). Further, this activity was measured in response to violin, piano and pure tones in 4-year-old children at the onset of music lessons and 1 year later, and compared to a second

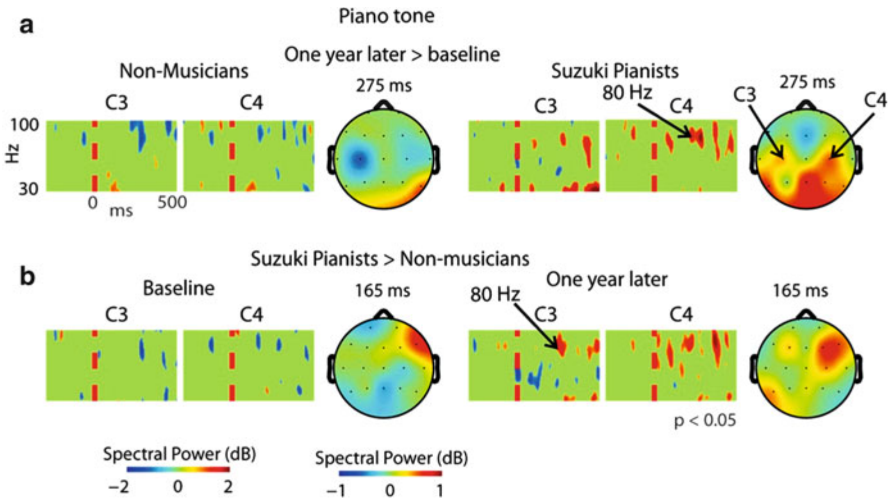


Fig. 8.8 Gamma band activity in 4- and 5-year-old children modulated by musical training. Induced gamma band activity (30–100 Hz) was derived from EEG recordings in response to piano tones measured in two groups of children (one beginning music lessons at the first measurement and the other not engaging in musical training) and at two time points 1 year apart (4 and 5 years of age). Zero ms represents the onset of piano tones. (**a**) Differences in gamma band activity across the year for the nonmusician children (*left*) and for the musician children (*right*). The musician children showed an increase in gamma band activity after a year, whereas the nonmusicians did not. As in adults, gamma band activity in response to a piano tone in musician children is long-lasting (at least 500 ms) and comes in waves, suggesting that it rides on a slower oscillatory process. (**b**) Differences in gamma band activity between the musician and nonmusician children at the first measurement (*left*) and at the second measurement a year later (*right*). At the first measurement there was no difference between groups, whereas by the second measurement, musician children showed greater gamma band activity compared to nonmusician children [From Trainor et al. (2009). Reprinted with permission of John Wiley & Sons]

group of children tested at the same two developmental time points (Fig. 8.8). None of the children showed significant gamma band activity at the first measurement. However, by the second measurement, gamma band activity was seen in the musician children but not in the control group (Shahin et al. 2008).

Together these studies of adult and child musicians suggest that formal musical training leads to the recruitment of more neurons and/or to increased synchronicity between neurons for the processing of isolated musical tones.

4.3 *Effects of Experience on Melodic Processing*

Melodies consist of sequences of tones and are composed within a musical system according to the tonal rules of that system. A sequence of melodic notes gives rise to expectations about what notes are more or less likely to follow. As discussed earlier, these expectations are learned through informal exposure to a musical system.

At the same time, there is substantial evidence that formal musical training greatly enhances melodic expectations.

More than half a decade ago, Meyer (1956) argued that the essence of musical meaning was in the degree to which musical expectations were realized or violated. In particular, meaningful violations set in motion physiological and psychological responses that give rise to emotional responses. One ERP component, the MMN, is generated in auditory cortex and reflects the operation of a mechanism for tracking expectations (see Picton et al. 2000; Näätänen et al. 2007; Trainor and Zatorre 2009). As described in Sect. 3.1, MMN occurs in response to virtually any type of sound change, including changes in pitch, duration, loudness, timbre, and spatial location. It also occurs, even in nonmusicians, in response to a change in a pattern of sounds, such as when occasional wrong notes are played in a melody that is presented in transposition to different starting notes (keys) from repetition to repetition (Trainor et al. 2002a).

MMN is typically of larger amplitude for melodic changes in adult musicians compared to nonmusicians (Fujioka et al. 2004). This enhancement for musicians extends to polyphonic contexts in which two melodies are played at the same time (Fujioka et al. 2005, 2008). Interestingly, for both musicians and nonmusicians, there was evidence that separate memory traces were formed in the brain for the two melodies, and that the representations were more robust for the higher-pitch melody, consistent with behavioral evidence of superior perception of the highest voice in polyphonic contexts (Crawley et al. 2002). While these studies suggest that formal musical training might enhance melodic processing in the brain, studies of young children are necessary in order to understand the relation between genetic and experiential factors.

There are few studies of the effects of musical training on melodic processing. However, Trainor et al. (2011) randomly assigned 4-month-old infants to one of two listening conditions. In one case, infants listened daily for a week to a CD of short children's melodies played in marimba timbre. In the other case, infants listened to the same melodies, but played in guitar timbre. Subsequently, ERPs were measured to occasional small changes in the pitch of a repeating tone when it was played in marimba timbre and when it was played in guitar timbre. They found that mismatch responses to the pitch change were larger for guitar than marimba tones only in the group exposed to guitar timbre at home, indicating that the musical experience led to more robust pitch responses for the familiarized timbre.

In sum, there is evidence of melodic processing differences between adult musicians and nonmusicians, but there are few studies in children to indicate the extent to which these differences are the result of musical training or due to genetic factors.

4.4 Effects of Experience on Acquisition of Key Membership and Harmony

As with cortical representations for isolated tones and for melodies, adult musicians show larger brain responses to syntactically unexpected chords (Koelsch et al. 2002b). Although the MMN response appears to be insensitive to key violations

(Trainor et al. 2002a; Fujioka et al. 2004, 2005), a similar response, the early right anterior negativity (ERAN) is sensitive to key and harmony violations in adults (Koelsch et al. 2001) even when factors such as amount of note repetition and degree of dissonance are controlled (Koelsch et al. 2007; Leino et al. 2007).

Three studies in children suggest that formal musical training accelerates acquisition of harmonic knowledge. Jentschke and Koelsch (2009) presented 11-year-old children with chord sequences and examined ERP responses when the last chord conformed to Western harmonic syntactic rules and when it did not. One group of participants were in the Saint Thomas Boys Choir in Leipzig and the other group were not training musically, although the two groups were matched for IQ and parents' education level. They found larger ERAN responses in the musician children, consistent with effects of musical training on the neural circuitry involved in harmonic processing, although of course the extent to which genetic differences contribute is not known.

Corrigall and Trainor (2009) examined two groups of 4- to 5-year-old children, one in which the children were just beginning music lessons and the other in which the children did not take lessons. Children were tested behaviorally at two time points, once before the onset of lessons and once approximately 8 months later. Children listened to sequences of five chords and judged whether each sequence sounded "good" or "bad." The sequences ended on either the tonic chord (i.e., conformed to Western harmonic structure), an out-of-key chord (tests key membership), or a chord that was within the key but not the expected harmony (tests harmonic syntax). Both groups showed some sensitivity to both key membership and harmonic syntax and the groups did not differ significantly at the first measurement. However, at the second measurement, the group taking music lessons showed superior performance, suggesting that early formal music lessons enhance harmonic processing.

Finally, there is evidence that musical training in infancy can accelerate knowledge of key membership (Gerry et al. 2010). In a comprehensive study, 6-month-old infants were randomly assigned to one of two types of music classes for a period of 6 months. The active music group received weekly lessons where parents and infants learned songs, moved to rhythms, and took turns with simple instruments such as little drums and xylophones. The passive group listened to Baby Einstein™ CDs in the background at their weekly lessons while infants and parents played at book, ball, block, and art stations. After 6 months of classes, when the infants were 12 months of age, they were given a battery of tests, including a test of sensitivity to musical keys. Infants were presented with two versions of an unfamiliar piano piece, one in its original form, and the other manipulated to alternate between two keys one semitone apart on every beat. This manipulation had the effect of making the second piece sound atonal because all 12 notes were present. Infants' preferences for the two versions were tested in a preference paradigm (see Sect. 3.2). The two groups differed significantly, with infants in the passive group showing no preference and infants in the active group preferring the original over the atonal version. Thus, when appropriate pedagogical approaches are used, music classes in infancy can accelerate acquisition of key membership. Because this study had random assignment to group, it can be inferred that the difference in musical experience caused the difference in the development of sensitivity to tonality. Thus, it can be concluded that formal training does affect musical outcome and that this training can be effective early in development. However, it remains unknown as to whether there are critical periods during which certain types of musical experience have the greatest effects.

5 Summary

Music is ubiquitous across cultures, and serves important functions, including emotional communication between infants, aiding general cognitive development, and promoting social cohesion and cooperation between individuals who make music together. Musical pitch structure has many levels. Individual tones have an absolute pitch level and tones are perceived relative to each other along the dimensions of pitch height, tone chroma (octave equivalence), and consonance and dissonance. In this chapter, it has been argued that musical pitch structure builds on these domain-general aspects of auditory processing, and that these aspects operate in similar ways across the different musical systems in the world. From a developmental perspective, these aspects of pitch operate early in development and reflect a combination of innate structural constraints, such as the response of the inner ear, and learning constraints, such as the fact that tonotopic maps do not develop normally in the absence of structured sound input. These aspects of pitch processing are not specific to music, and operate similarly in speech.

There are also aspects of musical pitch structure that are unique to music. These include the use of discrete pitch and a small number of pitch intervals per octave that define sets of scale notes that are used for musical composition. The domain-specificity of scales can be seen in that pitch changes in speech tend to be continuous and the exact sizes of pitch excursions in linguistic utterances are not critical. At this level of musical pitch structure there is considerable variation across musical systems in terms of the particular scales (intervals) used, in the probabilistic rules by which notes are combined into melodies, and in the meanings of particular note combinations. Developmentally, musical scales must be learned, just as a specific language must be learned. This learning appears to occur fairly early. The research evidence suggests that children as young as 3 or 4 years certainly have implicit knowledge of key membership, and that with musical training, some understanding of tonality can be seen as early as 12 months of age.

Some musical systems also have harmonic pitch structure, in which particular combinations of notes are sounded simultaneously to produce chords that are built on the various notes of the scale. Chord sequences have a sort of statistical syntax, in that the transitional probabilities of one chord following another are quite stable within a musical system. This aspect of musical pitch structure does not appear to be universal and brain areas beyond auditory cortex are recruited for harmony processing. Developmentally, sensitivity to harmony appears fairly late. Preschool children show sensitivity to some aspects of harmony, but a full lay understanding (i.e., implicit knowledge in musically untrained adults) does not appear to be complete until the early teenage years.

There is evidence that all aspects of music pitch processing are affected by learning and experience but, given a normal auditory environment in which to develop, the more complex culturally specific aspects appear to be more dependent on experience. Future developmental research involving non-Western musical pitch structures and participants familiar with such structures is necessary to corroborate current evidence regarding cultural specificity and experience, which is largely limited to Western structures and listeners. At the same time, musically trained and musically untrained adults appear to process musical pitch similarly. The difference between the groups appears to be one of sensitivity. Adults with musical training show larger brain areas devoted to musical processing and larger and earlier event-related potentials in response to musical stimuli. Furthermore, these training effects can be observed in young children. Musical training studies with random assignment are rare, but provide the most direct evidence of the role of experience. Indeed there is evidence that the earlier musical training begins, the larger the plastic changes that are possible, and that such experientially driven change can be seen prior to 1 year of age. Given the role of music in social, emotional and cognitive processes, musical experience in the early years likely helps to set children on an optimal developmental trajectory.

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