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PAPER

Children's implicit knowledge of harmony in Western music

E. Glenn Schellenberg,[1,3] Emmanuel Bigand,[2] Benedicte Poulin-Charronnat,[2] Cécilia Garnier[2] and Catherine Stevens[3]

1. *Department of Psychology, University of Toronto at Mississauga, Canada*
2. *LEAD CNRS, Université de Bourgogne, Dijon, France*
3. *MARCS Auditory Laboratories, University of Western Sydney, Australia*

Abstract

Three experiments examined children's knowledge of harmony in Western music. The children heard a series of chords followed by a final, target chord. In Experiment 1, French 6- and 11-year-olds judged whether the target was sung with the vowel /i/ or /u/. In Experiment 2, Australian 8- and 11-year-olds judged whether the target was played on a piano or a trumpet. In Experiment 3, Canadian 8- and 11-year-olds judged whether the target sounded good (i.e. consonant) or bad (dissonant). The target was either the most stable chord in the established musical key (i.e. the tonic, based on do*, the first note of the scale) or a less stable chord. Performance was faster (Experiments 1, 2 and 3) and more accurate (Experiment 3) when the target was the tonic chord. The findings confirm that children have implicit knowledge of syntactic functions that typify Western harmony.*

Introduction

Music, like language, is a universal behaviour with a communicative function. Music and language are both structured hierarchically with rules governing the order of events (Lerdahl & Jackendoff, 1983), and both systems vary from culture to culture. Despite these similarities in form and function, the music-acquisition process is relatively under-studied compared to language acquisition. In the present investigation, we examined knowledge of Western music among children from France, Australia and Canada. Although these countries have cultural differences, music based on the Western European tradition (including classical, folk, rock, blues, pop, etc.) predominates in each one. In other words, the investigation included a broad sampling of Western children but it was not cross-cultural in a musical sense.

In Western music, syntactic rules are related to its system of *tonality*. The use of major or minor scales means that some notes (e.g. the white notes on a piano) from the chromatic scale (i.e. all the notes on a piano) are more appropriate than other notes (e.g. the black notes) when a piece is in a particular key (e.g. C major). Specifically, each Western major and minor scale uses a seven-note subset of the 12 notes from the chromatic scale. The in-key notes (i.e. those from the scale) also form a hierarchy, with some notes more stable than others and better suited to end musical phrases. For example, notes that belong to the C major chord (C, E and G) are particularly stable in the key of C and therefore well suited to end phrases, with the tonic note (C, or *do*) the most stable of all (Krumhansl, 1990).

Although melody is a feature of all musical systems, Western music is unique in having elaborate rules governing *harmony*, which are related to rules of tonality. Harmony refers to the simultaneous combination of notes into chords and the sequential ordering of chords (i.e. chord progressions) (Aldwell & Schachter, 2003). In a Western musical key, seven chords (major, minor or diminished) can be defined, each based on a different degree of the scale. These chords form a hierarchy of stability in the key. The tonic chord (I) is the most stable; all other chords are perceived in relation to the tonic (Schenker, 1935; Lerdahl & Jackendoff, 1983). Chords based on the fourth and fifth scale degrees (referred to as subdominant and dominant chords, notated IV and V, respectively) are supplementary reference chords. These chords are of weaker importance than the tonic but are more referential and stable than the remaining chords from the key (Bharucha & Krumhansl, 1983; Lerdahl, 2001). For

Address for correspondence: Glenn Schellenberg, Department of Psychology, University of Toronto at Mississauga, Mississauga, ON, L5L 1C6, Canada; e-mail: g.schellenberg@utoronto.ca

example, in the key of C major, the C major chord (consisting of tones C, E and G) acts as the stable, referential tonic (I), whereas the F major chord (F, A and C) and G major chord (G, B and D), respectively, serve as the less stable, less referential subdominant (IV) and dominant (V). The relation between harmony and tonality is highlighted by the fact that the three tones of the tonic chord are also the most stable tones in the key.

Listeners with extensive training in music theory know explicitly that a dominant chord (V, based on *sol*, the fifth note of the scale) is typically followed by the related tonic chord (I, the chord based on *do*, the first note of the scale), particularly at the end of a musical piece. For musically untrained individuals, such knowledge is implicit rather than explicit. Nonetheless, previous findings make it clear that adults with no musical training have extensive implicit knowledge of Western harmony. In fact, they perform much like musically trained adults in some experimental paradigms (e.g. Bigand, Poulin, Tillmann, Madurell & D'Adamo, 2003; Francès, 1958). In *priming* studies, listeners hear a single chord (Bharucha & Stoeckig, 1986, 1987; Justus & Bharucha, 2001; Tekman & Bharucha, 1992, 1998; Tillmann & Bharucha, 2002) or an extended sequence of chords that conforms to a musical key (Bigand & Pineau, 1997; Bigand *et al.*, 2003; Bigand, Madurell, Tillmann & Pineau, 1999; Bigand, Tillmann, Poulin, D'Adamo & Madurell, 2001; Tillmann & Bigand, 2001; Tillmann, Bigand & Pineau, 1998). They are required to make a judgment – as quickly and accurately as possible – about a subsequently presented *target* chord. Judgments include deciding whether the target is in- or out-of-tune (Bharucha & Stoeckig, 1986, 1987; Justus & Bharucha, 2001; Tekman & Bharucha, 1992, 1998), pleasant (consonant) or unpleasant (dissonant) sounding (Bigand *et al.*, 1999, 2003; Bigand & Pineau, 1997), sung on one of two phonemes (Bigand *et al.*, 2001), played on one of two musical instruments (Tillman & Bigand, 2004), or whether its component tones are played in synchrony (Tillmann & Bharucha, 2002). In each case, the task requires participants to focus on the perceptual quality of the target chord rather than its harmonic relation to the prime.

All of these studies demonstrated *harmonic priming*. Processing of the target chord was facilitated (i.e. faster and/or more accurate) when it was closely related to the prime chord (e.g. when the prime and target stood in a V-I relation) or when it functioned as the tonic chord of the prime sequence rather than a less referential or stable chord. These findings suggest that harmonic processing is relatively automatic. Moreover, because the harmonic-priming effect is similar for musically trained and untrained listeners, subtle processing and understanding of Western harmony do not appear to require formal training in music. Rather, simple familiarization with a given musical idiom means that virtually all adults are *experienced* listeners (Lerdahl & Jackendoff, 1983). Our present goal was to test whether children are similarly experienced listeners.

In general, young infants appear to begin life as culture-free music listeners (e.g. Hannon & Trehub, 2005; Lynch, Eilers, Oller & Urbano, 1990), as they are with language (e.g. Kuhl, 2004; Werker & Lalonde, 1988). With increasing age and exposure to the music of their own culture, listeners find it easier to perceive and remember melodies that are structured like the music in their environment. For example, Lynch *et al.* (1990) presented a seven-note melody repeatedly to infants and adults. Infants were equally proficient at detecting when one note from the melody was mistuned (displaced in pitch), whether it comprised notes from a Western or a foreign (Javanese *pelog*) scale. By contrast, adults performed better with the native (Western) melody. Responses from 10- to 13-year-old children showed a modest advantage for the native melody that was more adult-like among children taking music lessons (Lynch & Eilers, 1991). Another study demonstrated that musical conventionality influenced adults' ability to form a stable representation of a melody, but this effect was attenuated for 5-year-olds and absent among 9-month-olds (Schellenberg & Trehub, 1999). In yet another study, adults but not infants were sensitive to the chord progressions suggested by a Western tonal melody (Trainor & Trehub, 1992).

Because Western tonality and harmony are culture-specific, one would expect these aspects of musical knowledge to show robust effects of exposure. In the most common method used to investigate knowledge of tonality (Krumhansl, 1990), listeners hear a stimulus that defines a musical key followed by one or two test tones. They are asked to rate how well the test tones fit with the established key, or how good the entire sequence (context plus test tones) sounds. In one such study, musically trained adults exhibited complete knowledge of the hierarchy of stability among notes but untrained adults did not (Krumhansl & Shepard, 1979). Rather, untrained listeners simply provided higher ratings for test tones that were proximate in pitch to the last tone of the context. In a follow-up investigation that included first- to sixth-grade children as well as adults (Krumhansl & Keil, 1982), younger children had a sense of key membership (i.e. in-key notes received higher ratings than out-of-key notes) but they made no distinctions among notes within a key. Older children distinguished some within-key notes (i.e. notes from the tonic chord) from others, but only adults distinguished the tonic from the other notes of the chord.

In Sloboda's (1985) study of listeners' knowledge of Western harmony, adults and children 5 to 11 years of age heard two chord sequences on each trial. One sequence was typical of Western musical structure. The other had the same chords presented in random order. The proportion of sequences identified appropriately (i.e. *correct* for typical order) was at chance levels for 5-year-olds but improved monotonically as a function of age. Other researchers have reported similar improvements in tonal knowledge with increases in age and formal training in music (e.g. Andrews & Dowling, 1991; Dowling, 1999; Lamont & Cross, 1994; Morrongiello, 1992; Zenatti, 1993). Considered as a whole, the findings reviewed above imply that Western musical knowledge develops gradually from infancy to adulthood, with some aspects dependent on formal instruction.

Other evidence suggests, however, that the musical enculturation process may not be so slow (Cuddy & Badertscher, 1987; Speer & Meeks, 1985). In one study of harmonic knowledge, 5- and 7-year-olds exhibited distinct neuronal activation patterns when anomalous chords were presented at the end of a sequence of chords that conformed to a musical key (Koelsch, Grossmann, Gunter, Hahne, Schrøger & Friederici, 2003). In another study (Trainor & Trehub, 1994), children and adults heard a 10-note melody presented repeatedly in transposition (i.e. at different pitch levels from presentation to presentation). Although the melody was simply a sequence of notes, it suggested specific harmonies, or combinations of notes. For example, the first three notes of the melody were members of the tonic chord (e.g. C_4-E_4-G_4), whereas the fourth, fifth and sixth notes (e.g. F_4-D_4-G_3) suggested a shift to the dominant-seventh (V^7) chord (e.g. G major with an added F note). An oddball (go/no-go) task was used to examine whether listeners could detect when one note was mistuned (displaced in pitch). Whereas 5-year-olds performed well only with out-of-key mistunings, adults *and* 7-year-olds performed well with the out-of-key and out-of-harmony mistunings. These results raise the possibility that implicit knowledge of some aspects of harmony is relatively well developed by 7 years of age.

Why does the musical enculturation process appear to be protracted in some instances but relatively quick in others? One explanation involves the use of outcome measures that tap either *explicit* or *implicit* musical knowledge. Judgments of *musicality* or *goodness* are explicit measures because they require direct evaluations of musical stimuli, even if listeners cannot articulate the basis for their judgments. By contrast, oddball judgments, evoked potentials and responses in priming tasks can vary as a function of implicit knowledge. It is well established that implicit measures are more sensitive than explicit measures. For example, when participants evaluate neutral stimuli, they give higher liking ratings to previously encountered stimuli than to novel stimuli, which indicates that they *remember* the encountered stimuli, at least subconsciously (for a review see Bornstein, 1989). Nonetheless, explicit measures of recognition for the same stimuli can be at chance levels. This independence between implicit and explicit measures of recognition is evident with both visual (e.g. Kunst-Wilson & Zajonc, 1980) and musical (e.g. Szpunar, Schellenberg & Pliner, 2004) stimuli. Thus, explicit measures may underestimate Western musical knowledge to varying degrees depending on the specific task. From this perspective, musical enculturation would appear to be relatively lengthy when explicit judgments are required but relatively brief when implicit knowledge is measured.

In three experiments, we examined the development of implicit knowledge of Western harmony. Our main objective was to test whether tonic chords have special status for child listeners. In contrast to Trainor and Trehub (1994), who examined implicit knowledge of harmonies suggested by melodies, we used audible chord progressions. In other words, our tests of harmonic knowledge were less abstract. They were also more subtle and nuanced because we did not introduce anomalous chords (Koelsch *et al.*, 2003) or tones (Trainor & Trehub, 1994) into a musical context. Rather, we asked whether children exhibit processing advantages for the most stable and referential chords in Western harmony compared to other, less stable chords.

Our use of implicit measures motivated the prediction that tonic target chords would be processed more efficiently than subdominant targets in the musical context established by the preceding (prime) chords. We also expected that older children would respond faster in general. On the one hand, the advantage for tonic chords might be greater among older children because of more exposure to music, and, consequently, more opportunity to learn rules of musical syntax. On the other hand, implicit knowledge of some aspects of Western harmony could be well developed relatively early in life, such that the advantage is similar across age groups.

General method

In each experiment, the children heard a series of chords (eight in Experiments 1 and 3, three in Experiment 2) and made a judgment about the perceptual quality of the final 'target' chord. They were not informed that the musical function of the target was manipulated in terms of its relation to the preceding (prime) sequence of chords. On half of the test trials, the target functioned as the tonic chord (I) of the prime sequence. On the other half, the target was a less stable chord in the context.

Because the principal outcome measure was response speed, children initially completed a series of training trials to ensure that they understood the task before beginning the actual test trials. In the training phase, children heard the same stimuli used subsequently as target chords, but the chords were presented one per trial. The children judged whether the chord was sung with the vowel /i/ or /u/ (Experiment 1), played on a piano or trumpet (Experiment 2) or consonant/dissonant (Experiment 3). Feedback indicated when responses were incorrect. The total number of training trials varied for individual children, ending when they mastered the task, which was defined as eight (Experiments 1 and 3) or four (Experiment 2) correct responses in succession (within a maximum of 40 trials). They subsequently proceeded to the test phase, during which they heard sequences of chords and made an identical judgment, as quickly and as accurately as possible, about the final chord. The training phase ensured that the task was relatively easy for children so that potential effects of the harmonic context on speed of responding could emerge. It also meant the accuracy levels (number correct) would be high during test trials, potentially at ceiling levels.

The analytic strategy was to test initially for the presence of harmonic priming by comparing responses to tonic target chords with those to less stable chords. Our prediction of enhanced processing for tonic chords motivated the use of one-tailed tests. Subsequent analyses examined differences between groups of participants using analysis of variance (ANOVA). Tests of main effects and interactions in the ANOVAs were two-tailed, including the main effect of harmonic priming.

Experiment 1

In the first experiment, stimulus chords were presented with synthesized, sung syllables, as in Bigand *et al.* (2001). French children 6 and 11 years of age heard a sequence of chords and judged whether the final, target chord was sung with the vowel /i/ or /u/. In the context of the preceding sequence, the target functioned as the stable tonic chord or the less stable subdominant chord.

Method

Participants

The listeners were 23 children from a middle-class neighbourhood in a small French city (Dijon). They were recruited from two age groups. One group (n = 10) consisted of first-grade children who were 6 years of age on average (M = 6 years, 3 months; SD = 3 months). Another group (n = 13) were 11 years old on average (M = 10 years, 11 months; SD = 2 months). The younger children had no music lessons except for those taught in public school. The older children had received formal, instrumental lessons at a small music conservatory (including ear training and playing in an orchestra) for an average of 3 years and 10 months (SD = 22 months) on one of a variety of musical instruments. In short, the design contrasted two groups of children who differed in incidental as well as formal exposure to music.

Apparatus

The chord sequences were played with voice sounds generated by VocalWriter 1.0 software. The sequences were recorded as high-quality digital sound files using SoundEdit software. Stimulus presentation and response recording were controlled with a customized program created with PsyScope software (Cohen, MacWhinney, Flatt & Provost, 1993) installed on a Macintosh computer. Children heard the stimuli over Sennheiser HD 200 headphones.

Stimuli

The stimuli came from Bigand *et al.* (2001). They consisted of 12 musical prime sequences (one for each major key) of six chords followed by two additional chords. Each chord comprised four notes presented with the same syllable.

The prime sequences defined the musical key. For each sequence, we generated two different two-chord endings (cadences) such that there were 24 sequences in total. Both endings formed a local authentic (perfect or V-I) cadence (e.g. G-C or C-F). In one, the 8th and final chord was the tonic (I) chord. In the other, it was the musically relevant but less stable subdominant (IV) chord (see Figure 1 for an example). The global context created by the first six chords defined the musical key and thus the harmonic function of the target chord. The sequences were composed in such a way that neither the tonic nor the subdominant chord occurred in the prime sequences. This feature eliminated possible confoundings between the target's musical function and its frequency of occurrence in the preceding context. Although all of the tones in the seven chords preceding the target were from the scale based on the tonic, subdominant targets actually shared more pitch classes with the contexts (M = 14.75) than did tonic targets (M = 12.50). In other words, if the context was in the key of C, the cumulative number of Fs, As and Cs was slightly higher than the cumulative number of Cs, Es and Gs. This aspect of the design ensured that any processing facilitation for tonic targets could not be attributed to low-level sensory factors (i.e. repetition priming). The tempo of the sequences was

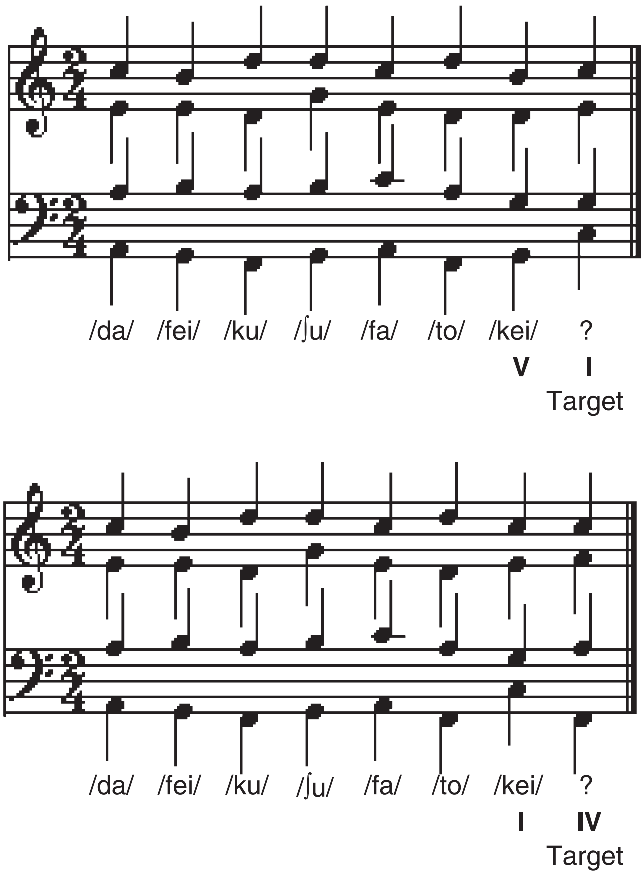

Figure 1 *Examples of stimuli from Experiment 1 in musical notation. Children judged whether the target (final) chord was sung with the vowel /i/ or /u/. The target functioned as the tonic (I) or the subdominant (IV) in relation to the preceding sequence of chords (upper and lower panels, respectively). In both cases, the final two chords formed a perfect cadence (V-I) at a local level. In relation to the musical key of the sequence, however, the final two chords in the lower panel formed a I-IV cadence.*

96 quarter tones per minute (i.e. 625 ms per chord). The duration of the target chord was limited to 2 seconds but it stopped sounding as soon as participants responded.

We used 24 different consonant-vowel syllables. The syllable for the eighth and final (i.e. target) chord was always /di/ or /du/. The remaining 22 syllables were assigned randomly to the first seven chords of the testing sequences. The vowels /i/ and /u/ were selected for the target syllables because they are the most easily distinguishable vowels generated by VocalWriter.

Procedure

Children were tested individually in a quiet room at their school. They responded directly onto the computer, pressing one key for /i/ and another for /u/. On each test trial, the children heard a sequence of eight chords and decided whether the final syllable (i.e. the final chord) contained the vowel /i/ or /u/. A feedback tone indicated when a response was incorrect. Crossing the 12 prime sequences with harmonic function (tonic or subdominant) and vowel (/i/ or /u/) of the target chord meant that there were 48 trials in total. Each child heard all 48 sequences presented in random order. The entire procedure took approximately 20 minutes.

Results and discussion

As expected, the children found it easy to identify the vowels correctly after reaching the training criterion. On average, the younger and older groups were 95.37% and 98.41% correct, respectively. These ceiling levels of performance precluded analysis of accuracy data. For analysis of response-time data, we calculated a mean response time (correct responses only) separately for each child for both conditions, excluding responses longer than 3 standard deviations from each child's overall mean. One 6-year-old was excluded because of random responding.

In preliminary analyses, paired t-tests confirmed that vowel identification was faster when the final syllable of the sequences was sung on the tonic rather than the subdominant chord, both for older children with musical training, $t(12) = 4.24$, $p < .005$ (by 100 ms on average), and for younger children with no music lessons, $t(8) = 3.01$, $p < .05$ (by 79 ms).

The main analysis involved a three-way mixed-design ANOVA, with one between-subjects variable (exposure to music) and two within-subjects variables (harmonic function, vowel). Descriptive statistics are illustrated in Figure 2. Performance was faster for tonic than for

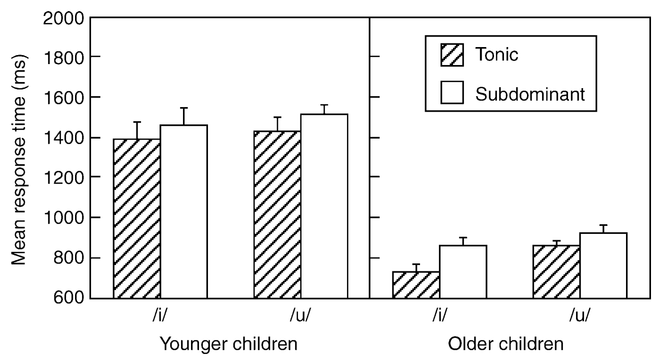

Figure 2 *Mean correct response times in Experiment 1 (French children) as a function of the relation of the target chord to the prime context, the target syllable, and age/exposure to music. Error bars are standard errors.*

subdominant targets, $F(1, 20) = 25.04$, $p < .001$, $MSE = 6817.731$. The older children also responded faster than younger children by approximately 600 ms, $F(1, 20) = 89.11$, $p < .001$, $MSE = 87310.102$, but even the older group took approximately 300 ms longer than the adults tested by Bigand *et al.* (2001). As in the earlier study, responses were faster (by approximately 75 ms) for /i/ than for /u/, $F(1, 20) = 6.76$, $p < .05$, $MSE = 16096.399$. Harmonic function did not interact with age, $F < 1$, and there were no other interactions.

These data replicate and extend the findings reported by Bigand *et al.* (2001). In their study of adult listeners, harmonic priming did not differ between graduate students registered at music conservatories and their counterparts who had no music lessons. Both groups responded faster to tonic over subdominant target chords. In the present study, we used the same method and observed an effect of harmonic context on vowel identification among children as young as 6 years of age. Although the absolute magnitude of this harmonic-priming effect was larger among older, musically trained children, the harmony manipulation did not interact significantly with age and exposure to music. These findings provide evidence that implicitly acquired knowledge of some aspects of Western harmony may be relatively well developed in the early school-age years.

Experiment 2

In Experiment 2, the sample included Australian children of two different age groups (7- and 8-year-olds; 10- and 11-year-olds). In each group, approximately half of the children had received formal lessons in music. In contrast to Experiment 1, the present experiment allowed us to disentangle potential effects of formal exposure from those of incidental exposure that occur simply as a consequence of age.

In the previous experiment, we used relatively long chord progressions as primes, the method favoured by Bigand and his colleagues (Bigand & Pineau, 1997; Bigand *et al.*, 1999, 2001, 2003; Tillmann & Bigand, 2001; Tillmann *et al.*, 1998). In the present experiment, we used much shorter, highly controlled primes similar to the ones used by Bharucha and his collaborators (Bharucha & Stoeckig, 1986, 1987; Justus & Bharucha, 2001; Tekman & Bharucha, 1992, 1998; Tillmann & Bharucha, 2002). In two testing conditions, the prime consisted of two chords, both of which shared exactly one tone with the target chord. In half of the trials, the two prime chords had a strong harmonic relation to the target (IV-V-I). In the other half, the relation was harmonically ambiguous (Flat VI-Flat III-I). The prime chords were constructed with tones of indeterminate pitch height ('Shepard tones'), which eliminated the possibility that voice-leading (e.g. the highest voice in the sequences) could differ across the priming and no-priming conditions, as it did in Experiment 1. In contrast to the vowel-identification task of Experiment 1, children judged whether the target chord was played on a *piano* or *trumpet*.

Method

Participants

The listeners were 36 children recruited from middle-class suburban areas in a large Australian city (Sydney). Approximately half ($n = 19$) were 10- and 11-year-olds (M = 10 years, 11 months; SD = 7 months). The other half ($n = 17$) were 7- and 8-year-olds (M = 8 years, 4 months; SD = 4 months). Twenty children (10 in each age group) had virtually no training in music (i.e. 1 month or less) outside of school. The other, musically trained children had music lessons that included a variety of musical instruments and instructional methods. On average, the older, musically trained children ($n = 9$) had 2 years and 10 months of formal music lessons outside of school (SD = 20 months), whereas the younger, musically trained children ($n = 7$) had 2 years of lessons (SD = 20 months).

Apparatus

The apparatus was identical to Experiment 1 except for the brand of headphones (Koss UR 120).

Stimuli

The target chords were 1-s, three-tone major chords in root position (lowest tone = *do*, middle tone = *mi*, highest tone = *sol*), which meant that the middle and highest tones were 4 and 7 semitones higher than the lowest tone, respectively. Twelve targets were presented in a piano timbre, which was generated using the Piano 1 waveform on a Roland XV-5080 digital workstation. Another 12 were presented with a trumpet timbre (Trumpet 1 waveform). The lowest tone of each piano and trumpet chord ranged from C_4 (middle C) to B_4 (11 semitones higher), such that there were 12 different target chords for each timbre, corresponding to the 12 major scales.

The prime contexts consisted of two 1-s chords. In the *priming* condition, the chords were the subdominant and dominant of the tonic target, such that the prime and target chords formed a typical IV-V-I chord progression, which is known to instantiate a strong sense of musical key (Krumhansl & Kessler, 1982). Both chords shared one pitch-class with the target chord. For example, if the target chord was C major with pitch classes C, E and G, the subdominant (IV) chord (F major) had pitch classes F, A and C, whereas the dominant (V) chord (G major) had G, B and D. In the *no-priming* condition, target chords were preceded by two major chords that had identical overlap in terms of pitch class, but the three-chord sequences did not represent a typical chord progression in Western music. For example, for the C-major target chord, the first prime chord was A-flat major (with pitch classes A-flat, C and E-flat) and the second chord was E-flat major (E-flat, G and B-flat). A 100-ms silent interval separated the first two (prime) chords and the target chord from the second prime chord. All stimuli were saved as high-quality digital sound files.

The two chords in the prime context consisted of three *Shepard tones* (Shepard, 1964), which have indeterminate pitch height such that there is no difference between root position, first inversion and second inversion (i.e. tones from lowest to highest arranged *do-mi-sol*, *mi-sol-do* or *sol-do-mi*, respectively). Each of 12 Shepard tones was constructed with 10 pure tones (sine waves) generated with SoundEdit software. Each Shepard tone consisted of all pure tones of a particular pitch class that fell between 20 and 20,000 Hz, which corresponds to the frequency range of normal human hearing (Moore, 1997). The amplitude spectrum for each Shepard tone was adjusted so that component tones in the mid-range (i.e. 382 to 873 Hz) had maximum amplitude, tones increasingly lower and higher had increasingly reduced amplitude, and the lowest and highest tones had minimal amplitude. Pilot testing indicated that the endlessly ascending and descending 'Shepard illusion' (Shepard, 1964) was robust with this set of tones.

Procedure

The children were tested individually in a quiet room at their school. Children heard three chords on each trial and judged whether the third and final chord had a piano or a trumpet sound. Each of the 24 target chords was preceded by two Shepard-tone chords, which formed either a typical (priming condition) or an atypical (no-priming condition) chord progression in Western music. In addition, each trial began with all 12 Shepard tones presented in random order (200 ms each) followed by a 1-s silent interval to eliminate the possibility of carry-over effects from trial to trial. The 48 trials were presented in random order. Feedback (correct or incorrect) was provided after each response. The entire procedure took approximately 15 minutes.

Results and discussion

After completing the training phase, the instrument-identification task was easy for the children and performance accuracy was at ceiling levels, as it was in Experiment 1. On average, performance in each of the four testing conditions (priming/piano, priming/trumpet, no-priming/piano and no-priming/trumpet) was 92.5% correct or higher (i.e. better than 11 out of 12 correct).

The dependent variable in the main analysis was correct response times, which were calculated separately for each child for each of the four conditions. As in Experiment 1, responses longer than 3 standard deviations from each child's mean were excluded from consideration. Although there was a general advantage for the priming conditions over the no-priming conditions, $t(35) = 2.05$, $p < .05$, preliminary tests indicated that the harmonic-priming manipulation was not significant when any of the four groups of children was analysed separately. A separate analysis revealed that musical training had no effect on response times and did not interact with any other variable (i.e. age, priming or timbre) or combination of variables. Thus, it was not considered further. The low threshold for classification as musically trained (i.e. some lessons) likely reduced power to detect differential responding based on training. Nonetheless, even large differences in training among adults can have minimal influence on response patterns in harmonic-priming tasks (Bigand *et al.*, 2001, 2003; Tillmann & Bigand, 2001; Tillmann *et al.*, 1998).

A three-way (age group × priming × timbre) mixed-design ANOVA revealed three significant main effects. Descriptive statistics are illustrated in Figure 3. As expected, older children responded faster than younger children by approximately 400 ms on average, $F(1, 34) =$

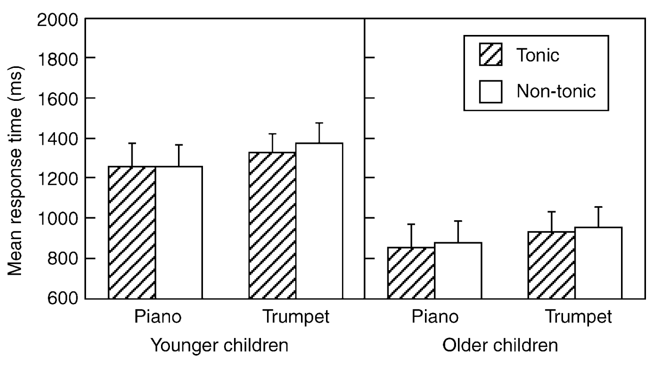

Figure 3 *Mean correct response times in Experiment 2 (Australian children) as a function of the relation of the target chord to the prime context, the target instrument, and age. Error bars are standard errors.*

8.62, $p < .01$, $MSE = 663676.733$. Children were also quicker (by approximately 80 ms) to identify piano target chords compared to trumpet chords, $F(1, 34) = 10.41$, $p < .005$, $MSE = 24283.426$, presumably because piano tones have a more rapid onset time due to the percussive nature of the instrument. The effect of the priming manipulation was also reliable, $F(1, 34) = 4.15$, $p < .05$, $MSE = 4245.388$. On average, children were 22 ms faster at identifying the timbre of the target chord when the chord represented a conclusion to a typical rather than an atypical Western chord progression. The effect appears to be smaller in magnitude than in Experiment 1 (compare Figures 2 and 3), however, and virtually absent when younger children responded to piano chords. Nonetheless, there was no interaction between the priming manipulation and age and no three-way interaction, Fs < 1. In other words, the results point to a small but general effect that did not increase with additional age or exposure to music. In sum, we again found evidence of implicit knowledge of Western harmony by age 7, even among children with no formal training in music.

Experiment 3

Experiments 1 and 2 provided evidence of harmonic priming among young children from France and Australia. This effect could not be attributed to formal training in music, to differences in voice leading between the priming and no-priming conditions, or to the number of notes in the prime sequence that overlapped with those of the target chord. In Experiment 3, the method was similar to that of Experiment 1 but we examined whether more efficient processing of tonic compared to subdominant target chords would be evident even when a subdominant chord occurred in the prime context.

To make the results as general as possible, we tested children from a third country in a task different from those used in Experiments 1 and 2. Musically trained and untrained Canadian children from two age groups (7- and 8-year-olds, 10- and 11-year-olds) were required to identify whether the final target chord sounded *good* (consonant) or *bad* (dissonant) based on its degree of sensory consonance (i.e. not on its relation to the prime context). To increase power to detect differential responding due to musical training, the classification criteria were more conservative than they were in Experiment 2. To be classified as musically trained, the older children had at least 2 years of music lessons, whereas the younger children had at least 1 year. The musically untrained children had no music lessons outside of school.

Method

Participants

The participants were 44 children recruited from a middle-class area surrounding a suburban college campus in a large Canadian city (Toronto). Half of the children were 10 or 11 years of age (M = 11 years, 0 months; SD = 7 months). Recruitment of these *older* children was limited to those who fell into one of two groups: at least 2 years of formal music lessons (M = 4 years, 4 months; SD = 24 months; $n = 13$) or no music lessons outside of school ($n = 9$). A *younger* group comprised 22 7- and 8-year-olds (M = 8 years, 1 month; SD = 6 months). Half had at least 1 year of music lessons (M = 1 year, 10 months; SD = 9 months; $n = 11$). The other half had no lessons ($n = 11$). For both age groups, formal training in music included a variety of musical instruments and instructional methods.

Apparatus

The apparatus was identical to Experiments 1 and 2 except that the stimuli were presented over Sony MDR-CD370 headphones.

Stimuli

The stimuli in the test phase were sequences of eight chords taken from Bigand *et al.* (2003). Half of these were constructed identically to those of Experiment 1 (see Figure 1), but presented with a piano timbre (produced by an ETM10 Yamaha Sound Expander) instead of synthesized voices. The remaining stimuli were modified slightly. In all cases, the first seven chords were played at a tempo of 96 quarter notes per minute, such that chord onset asynchrony was 660 ms. The 12 prime sequences from Experiment 1 (one for each major key) were each followed by two different two-chord cadences. As before, the final two chords served both as a dominant-tonic (V-I) and as a tonic-subdominant (I-IV) cadence.

The occurrence of the subdominant chord in the prime context was also manipulated, such that there were 48 (2×24) experimental chord sequences. In the *no-target-in-context* condition, the targets (tonic and subdominant) never occurred in the prime context, as in Experiment 1. In the *subdominant-in-context* condition, the subdominant chord (but not the tonic chord) occurred once or twice in the context. Compared to tonic targets, subdominant targets shared more notes and pitch classes with the prime contexts in the subdominant-in-context condition ($M = 18.58$ compared to

M = 14.75). This difference was exaggerated compared to the no-target-in-context condition (see Experiment 1), which made the test of harmonic priming even more conservative.

The target chord was *consonant* (pleasant sounding) in half of the trials. It was rendered *dissonant* in the other half by adding a tone that was 1 semitone above the tonic or the fifth of the target chord (e.g. either the tone C# or G# was added to the C chord consisting of the tones C-E-G). As in Bigand *et al.* (2003), the additional dissonance-creating tone was presented with decreased amplitude (−4 dB). In sum, the testing stimuli comprised 96 different chord sequences in total (12 prime contexts × 2 cadential endings × presence/absence of subdominant in the context × consonance/dissonance of target chord).

Procedure

Children were tested individually in a sound-attenuating booth. They heard sequences of eight chords and judged whether the eighth and final chord sounded good or bad. To ensure that there were no carry-over effects from trial to trial, each chord sequence was preceded by a sequence of 12 pure tones from the chromatic scale presented in random order. To limit the number of trials and the possibility of fatigue, each child was tested with 48 sequences (half of the 96 created), 24 ending in a consonant chord and 24 ending in a dissonant chord. The specific target chords (consonant or dissonant) were switched (to dissonant or consonant, respectively) for half of the children. In both halves, the consonance/dissonance manipulation was counterbalanced with the harmonic-function manipulation.

Results and discussion

The dissonant chords do not correspond to lawful musical events in Western tonal music. Thus, no straightforward prediction can be made for these trials and the analyses were restricted to the consonant trials. Proportions of correct responses are provided in Table 1. In contrast to Experiments 1 and 2, performance accuracy was below ceiling levels, which indicates that the present task was more difficult than the previous two even after children reached the training criterion. Arcsine transformations of proportions were analysed. Preliminary analyses compared performance accuracy between tonic and subdominant target chords separately for each of the four groups of children. Performance was reliably more accurate for tonic chords among the older, untrained children, $t(8) = 2.85$, $p < .05$, and among the younger, untrained children, $t(10) = 1.83$, $p < .05$. There was no advantage for tonic chords among either of the musically trained groups.

A 2 × 2 × 2 × 2 mixed-design ANOVA with 2 between-subjects variables (age group, musical training) and 2 within-subjects variables (harmonic function of the target chord, occurrence of the subdominant in the prime context) revealed a main effect of age. Older children made more correct responses than the younger children, $F(1, 40) = 11.89$, $p < .005$, $MSE = .780$. In general, correct responses were also more numerous for tonic targets than for subdominant targets, $F(1, 40) = 9.91$, $p < .005$, $MSE = .104$. This effect was qualified, however, by a significant interaction between harmonic function and musical training, $F(1, 40) = 6.89$, $p < .05$, $MSE = .104$. Follow-up tests revealed that musically untrained children were more accurate when making judgments about tonic compared to subdominant target chords, $F(1, 18) = 12.11$, $p < .005$, MSE = .131, an advantage that was absent among the trained group, $F < 1$. In short, music lessons appear to have made performance accuracy insensitive to the harmonic-priming manipulation. Age did not interact with harmonic function of the target chord, $F < 1$, and there were no other interactions.

The next set of analyses examined correct response times. The results are illustrated in Figure 4. As in Experiments 1 and 2, for each child we calculated a mean response time for each of the four conditions, excluding any response times that were more than 3 standard deviations from the child's overall mean. Data from five children were excluded from the analysis because of empty cells (no correct responses in one or

Table 1 *Mean performance accuracy measured as percentage correct in Experiment 3 (Canadian children, consonant trials) as a function of target chord, prime context, age group, and musical training (Standard errors are in parentheses)*

	No target in context		Subdominant in context	
	Target	Subdominant	Tonic	Subdominant
Younger, untrained	59.1 (9.4)	48.5 (8.6)	57.6 (10.9)	47.0 (8.7)
Younger, trained	60.6 (9.1)	57.6 (11.1)	62.1 (10.3)	50.0 (11.7)
Older, untrained	85.2 (9.4)	72.2 (7.4)	85.2 (7.6)	66.7 (9.2)
Older, trained	87.2 (6.6)	84.6 (8.1)	87.2 (7.8)	87.2 (7.8)

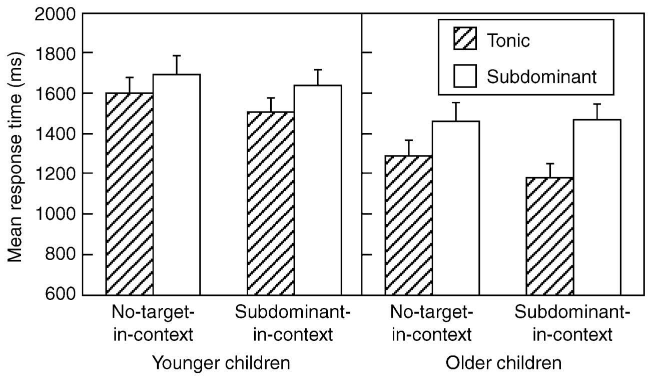

Figure 4 *Mean correct response times in Experiment 3 (Canadian children) as a function of the relation of the target chord to the prime context, the presence of the subdominant in the context, and age. Error bars are standard errors.*

more of the four conditions). Preliminary analyses revealed faster responding for tonic over subdominant target chords for the older, musically trained group, $t(11) = 3.79$, $p < .005$ (by 208 ms on average), the older-untrained group, $t(8) = 2.39$, $p < .05$ (274 ms), the younger-trained group, $t(8) = 2.68$, $p < .05$ (218 ms), but not for the younger-untrained group (10 ms).

An ANOVA confirmed that responses were faster for older compared to younger children, $F(1, 35) = 8.18$, $p < .01$, $MSE = 290478.168$, but this effect was qualified by a two-way interaction between age group and musical training, $F(1, 35) = 6.97$, $p < .05$, $MSE = 290478.168$. In the older group, the musically trained children were, on average, approximately 300 ms faster than the untrained children, $F(1, 19) = 5.15$, $p < .05$, $MSE = 342364.157$, but still approximately 500 ms slower than the adults tested by Bigand *et al.* (2003). In the younger group, response times of trained and untrained children did not differ ($p > .15$). In other words, music lessons predicted faster performance provided they were substantial in duration (2 years or more) and the children were more mature. Bigand *et al.* also found that musically trained adults responded faster than their untrained counterparts. Indeed, advantages on music-related tasks for musicians are relatively widespread for adult listeners (e.g. Dowling & Harwood, 1986; Krumhansl & Shepard, 1979; Lynch *et al.*, 1990). Presumably, in addition to being more difficult, our consonance-identification task was a more *musical* measure than identifying vowels (Experiment 1) or instruments (Experiment 2).

A small but significant main effect revealed that responding was approximately 65 ms faster when the subdominant was present in the prime sequence, $F(1, 35) = 4.52$, $p < .05$, $MSE = 34117.298$. This effect was not evident among the adults tested by Bigand *et al.* (2003). The presence or absence of the subdominant in the primes did not interact, however, with the type of target chord (tonic or subdominant), $F < 1$. In other words, responses to tonic *and* subdominant target chords were relatively quick when the subdominant chord was in the previous context. One possibility is that the presence of the subdominant chord contributed to the identification of the musical key and the tonal centre. Because the prime sequences never contained a tonic chord, they contained several minor chords (from the tonic key) and sounded somewhat like *modal* music (i.e. church music from the Renaissance). Although music theory proposes that some minor and major chords are functionally equivalent (e.g. ii and IV, which have two notes in common), the children in the present experiment may not have perceived this equivalence. Instead, the sequences may have contained some tonal ambiguity until the subdominant chord instilled a stronger sense of key, which resulted in faster processing for both target chords.

In line with our primary hypothesis, responding was approximately 180 ms faster for tonic targets than for subdominant targets, $F(1, 35) = 14.60$, $p < .001$, $MSE = 82680.606$. This effect did not interact with age ($p > .15$) or musical training ($F < 1$). In many aspects, these findings with musically trained and untrained children replicate those of Bigand *et al.* (2003) with trained and untrained adults. Harmonic-priming effects (re: accuracy or speed, or both) were evident for each of the four groups of children. Specifically, target chords were processed more accurately and/or more quickly when the targets acted as tonic rather than subdominant chords in a musical context. Although subdominant target chords sometimes occurred in the priming sequences, tonic targets were still more implied by the musical contexts. Implicit knowledge of Western musical structure appears to have allowed the children to abstract a tonal centre (i.e. the tonic) from a complex sequence of chords, and, consequently, to expect that the sequence would end with the tonic chord.

As in the previous experiment, harmonic priming was not enhanced significantly by additional exposure to music, whether formal (through music lessons) or informal (through increased incidental exposure as a consequence of age). Nonetheless, in contrast to Experiments 1 and 2, the present findings provided some evidence of the role of exposure in the music-acquisition process. When the four groups of children were analysed separately, the response-speed advantage for tonic over subdominant target chords was evident for all of the groups except the younger, untrained children. This pattern implies that formal *and* informal exposure to music accelerates the learning process. The lack of an interaction between the priming manipulation and exposure may be a consequence of a lack of statistical power.

General discussion

In three experiments, children without music lessons demonstrated implicit knowledge of syntactic rules that govern harmony in Western music. In all cases, processing of a target chord was facilitated when it functioned as a tonic chord (the chord based on *do*, the first scale degree) rather than a less stable chord in relation to a preceding sequence of chords. Such facilitation was evident in faster responding (Experiments 1, 2 and 3) and in more accurate performance (Experiment 3). The findings generalized across three different stimulus contexts, three different priming tasks, and children from three different countries. Across experiments, the design ensured that the effects could not be attributed to simple sensory factors (e.g. repeated tones). Moreover, the harmonic-priming effects were not enhanced reliably by additional exposure to music, whether *formal* through music lessons or *incidental* through increases in accumulated music listening that accompany development. Thus, implicit knowledge of basic harmonic functions is evident and relatively complete among children of 6 and 7 years of age who have no musical training. This finding complements and extends previous findings indicating that harmonic-priming effects are similar among musically trained and untrained adults (Bharucha & Stoeckig, 1986, 1987; Bigand *et al.*, 1999, 2001, 2003), and that 7-year-olds have adult-like understanding of harmonies suggested by melodies (Trainor & Trehub, 1994). It also highlights the utility of implicit measures in measuring musical knowledge that is common to virtually everyone. Previous findings indicating a protracted acquisition process are likely to be a consequence, at least in part, of testing knowledge that must be articulated explicitly.

How do young children without music lessons acquire knowledge of Western harmony? Regular exposure could be the principal explanatory factor (e.g. Tillmann, Bharucha & Bigand, 2000). Many children hear music on a daily basis at home or in the car, as well as the theme songs and other music that accompany children's television shows and films. Singing is also common in school, among families, and as part of children's games, and mothers and other caregivers sing to young infants and children regularly in virtually all cultures (Trehub & Trainor, 1998). Child-directed songs are also notable for their faithful adherence to a single musical key. In Dowling's (1988) survey, 93% of nursery songs had no notes that came from outside the starting key. Hence, regular exposure to musical structures that conform to musical keys could lead to rapid learning of such structures, including implicit knowledge of a reference tone (tonic, or *do*) and the chord built on this tone.

According to Reber (1992), humans become sensitive to structure in a complex environment through simple, passive exposure to regularities. Notably, such learning is often inaccessible to deductive reasoning. In contrast to knowledge acquired explicitly, there is evidence that implicit knowledge is: (1) remembered for longer periods of time (Allen & Reber, 1980), (2) relatively insensitive to individual differences in age and IQ (Reber, Walkenfeld & Hernstadt, 1991), and (3) more resistant to cognitive and neurological disorders (Abrams & Reber, 1988). In one study (Reber, 1993), 4-year-olds and 14-year-olds performed similarly on a measure of implicit learning. In another study (Don, Schellenberg, Reber, DiGirolama & Wang, 2003), children and adults with Williams Syndrome (mean IQ approximately 65) demonstrated implicit learning of an artificial grammar. The present findings are consistent with Reber's account of implicit learning, and with Karmiloff-Smith's (1992, 1994) developmental perspective as applied to music. Implicit knowledge of Western harmony is likely to represent an initial, relatively low-level stage of representation, which could then develop into a higher-level, explicit representation with formal training in music.

The present results are further contextualized by recent evidence of the perceptual and cognitive mechanisms that facilitate early language acquisition. In one study (Saffran, Aslin & Newport, 1996), 8-month-olds demonstrated sensitivity to statistical regularities in speech after a mere 2 min of exposure to a continuous string of synthesized syllables. Identical response patterns were evident when the stimuli were changed from syllables to pure tones (Saffran, Johnson, Aslin & Newport, 1999). In another study, 7-month-olds demonstrated sensitivity to rules of order in language after hearing 2 min of a highly simplified, artificial grammar (Marcus, Vijayan, Bandi Rao & Vishton, 1999). Because 7- and 8-month-olds demonstrate short-term memory for rules of order after 2 min of exposure to computer-generated syllables or pure tones, perhaps it should come as no surprise that young children demonstrate long-term memory for harmonic rules of order after 6 or 7 years of incidental exposure to meaningful musical materials.

Because harmony is specific to Western music, knowledge of Western harmony is obviously learned. Why, then, were effects of exposure in the present investigation either weak (Experiment 3) or non-existent (Experiments 1 and 2)? One possibility is that the sensitivity of the outcome measures to implicit knowledge made them relatively insensitive to more subtle differences in amount of knowledge. Moreover, response times from children are bound to be particularly noisy, with factors such as motivation playing a major role. The training sessions also ensured that children performed the tasks relatively easily and quickly, possibly at over-learned levels, which could explain why the only task with below-ceiling levels of accuracy (Experiment 3) also provided the best (but still weak) evidence of effects of exposure on response times.

Another possibility is that Western harmony is based on processing biases that make it relatively easy to learn. Across cultures, musical systems share many features that appear to stem from processing predispositions and constraints rather than mere coincidence (Trehub, 2000, 2003; Thompson & Schellenberg, 2002). For example, musical scales tend to have unequal steps (i.e. unequal intervals between adjacent tones) (Burns, 1999), they typically use between five and seven tones per octave (Dowling & Harwood, 1986), and consecutive tones in melodies tend to be close in pitch (Vos & Troost, 1989). The first feature allows scales to have a tonic (*do*) or reference tone (Balzano, 1982), and infants exhibit processing advantages for native *and* nonnative scales with unequal steps compared to scales with equal steps (Trehub, Schellenberg & Kamenetsky, 1999). The second and third features, respectively, appear to stem from limitations in the capacity of working memory (Miller, 1956), and a perceptual tendency to form groups based on the Gestalt principle of proximity (Narmour, 1990; Schellenberg, 1997). Listeners of different ages and cultural backgrounds expect that the next tone in a melody will be proximate to the tone they just heard (Schellenberg, 1996; Schellenberg, Adachi, Purdy & McKinnon, 2002).

Perceptual biases for particular tone relations are especially relevant to the acquisition of harmonic knowledge. Tones related by small-integer frequency ratios (e.g. octave – 2:1, perfect fifth – 3:2, perfect fourth – 4:3) are present in scales from a variety of musical cultures, and infant, child and adult listeners find intervals (i.e. tone pairs) with these relations easier to perceive and remember than intervals with large-integer ratios (e.g. tritone – 45:32, major seventh – 15:8, minor ninth – 32:15; Schellenberg & Trehub, 1994a, 1994b, 1996a, 1996b; Trainor, 1997). Young infants also notice similarities between different intervals with small-integer frequency ratios, such as perfect fifths and fourths, which make them distinct from other intervals, such as tritones (Schellenberg & Trainor, 1996).

Perfect fifths and fourths play important structural roles in Western tonality and harmony. Chords with tonic notes separated by these intervals (tonic and subdominant, tonic and dominant) are 'closely related' in music theory (Aldwell & Schachter, 2003). In fact, the underlying scales are identical except for one tone. To illustrate, G and C major chords are closely related: G is a perfect fifth above C (and a perfect fourth below C), and six of the seven notes in the G major scale are present in the C major scale (i.e. all but F-sharp). The entire set of pitch classes for any major scale can also be recovered by starting at any tone and successively adding tones a perfect fifth higher (or a perfect fourth lower) until a set of seven tones is accumulated (e.g. tones F, C, G, D, A, E, B form the C-major scale). In short, Western harmony and tonality – although specific to Western music – are not constructed arbitrarily with respect to perceptual predispositions. This observation helps to explain why the music-acquisition process is easier and faster than one might otherwise expect.

Although contributions from nature facilitate the music-acquisition process among young listeners, many aspects of Western tonal music (e.g. hierarchical pitch and temporal structures, other dimensions that vary simultaneously such as timbre and amplitude) are bound to represent significant challenges. In a multidimensional structure such as music, the particular dimensions that are perceived and related to other dimensions depend on the listener's cognitive capabilities (Stevens & Gallagher, 2004). Over development, an identical musical stimulus would be perceived, segmented, chunked and compared in increasingly complex ways (e.g. from simply perceiving the beat to following the intricate weaving of voices in a four-part fugue). Musical training is likely to facilitate this process by providing explicit labels for concepts and relations (Ratterman & Gentner, 1998) and by providing tools to analyse, organize and compare musical structures. Even listeners without music lessons would become sensitive to invariant relations (re: contour, intervals, rhythm, harmony) when they hear the same piece sung with different words (e.g. *The Alphabet Song, Twinkle twinkle little star, Ba ba black sheep* share the same melody) and voices, or performed at different speeds, on different instruments, with different harmonic accompaniment, and so on.

In sum, acquisition of musical knowledge, like language acquisition (Hoff, 2005; Tomasello, 2003), is best considered from an interactionist perspective, with contributions from both nature and nurture. Although Western harmony is unique in specifying rules governing simultaneous combinations of tones, it incorporates many features that harness processing predispositions, including those that are relatively general (e.g. sensitivity to structural regularities) as well as those that are music specific (e.g. processing advantages for small-integer frequency ratios). This dependence on natural abilities would make harmonic rules relatively easy to learn simply from incidental exposure to music that the average child experiences. Nonetheless, the ease and rapidity of the music-acquisition process belie the claim that music has no adaptive significance (Pinker, 1997). The adaptive relevance of music may be less obvious than other domains in which development occurs quickly and effortlessly (e.g. language, walking), but it is doubtful that music would differ qualitatively in this regard.

Consider the important role of music in social bonding in general (DeNora, 2000), and between infants and caregivers in particular (Dissanayake, 2000). Moreover, there is now a wide body of evidence that the brain has specialized areas for music processing (Peretz, 2003; Peretz & Coltheart, 2003; Peretz & Hyde, 2003), and that these areas are similar for musicians and nonmusicians (Koelsch, Gunter, Friederici & Schroeger, 2000). Neurological studies also reveal that specific aspects of music and language processing may be subserved by the same regions (Maess, Koelsch, Gunter & Friederici, 2001), and that music primes linguistic concepts much as words do (Koelsch, Kasper, Sammler, Schulze, Gunter & Friederici, 2004). Indeed, there has been much recent speculation on the evolutionary origins of music (for a review, see Wallin, Merker & Brown, 2000), and on relations between music and language (McMullen & Saffran, 2004; Patel, 2003; Thompson, Schellenberg & Husain, 2003, 2004).

It is well established that by the age of 4, typically developing children have acquired substantial knowledge of the syntactic rules of their native language (e.g. Hoff, 2005). The data reported here provide evidence that some syntactic rules in music are acquired by age 6. Future studies of even younger children could help to further our understanding of the similarities and differences between the language- and music-acquisition processes. This line of research could also improve our knowledge of the development of communicative and social behaviours in general, and the relative importance of language and music in human evolution.

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