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PAPER

Enculturation to musical pitch structure in young children: evidence from behavioral and electrophysiological methods

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Abstract

Children learn the structure of the music of their culture similarly to how they learn the language to which they are exposed in their daily environment. Furthermore, as with language, children acquire this musical knowledge without formal instruction. Two critical aspects of musical pitch structure in Western tonal music are key membership (understanding which notes belong in a key and which do not) and harmony (understanding which notes combine to form chords and which notes and chords tend to follow others). The early developmental trajectory of the acquisition of this knowledge remains unclear, in part because of the difficulty of testing young children. In two experiments, we investigated 4- and 5-year-olds' enculturation to Western musical pitch using a novel age-appropriate and engaging behavioral task (Experiment 1) and electroencephalography (EEG; Experiment 2). In Experiment 1 we found behavioral evidence that 5-year-olds were sensitive to key membership but not to harmony, and no evidence that 4-year-olds were sensitive to either. However, in Experiment 2 we found neurophysiological evidence that 4-year-olds were sensitive to both key membership and harmony. Our results suggest that musical enculturation has a long developmental trajectory, and that children may have some knowledge of key membership and harmony before that knowledge can be expressed through explicit behavioral judgments.

Research highlights

- Behavioral sensitivity to Western tonal structure increases between 4 and 5 years of age.
- Four-year-old children show sensitivity to Western key and harmony structure when measured with preconscious event-related potential components but not in overt behavior.
- Acquisition of Western musical structure through everyday exposure has a long developmental trajectory.

Introduction

Sophisticated musical knowledge is often attributed solely to accomplished musicians, but studies indicate that non-musicians possess considerable implicit musical knowledge. Even adults who have never played a musical instrument can typically tap to a beat, sing a familiar song, detect a wrong note in an unfamiliar piece of music from their culture, and experience the subtle emotions conveyed by music (Jackendoff & Lerdahl, 2006; Miller, 2000). Furthermore, children acquire knowledge of the musical structure of their culture through everyday exposure, similar to the way that they learn their native language. In contrast to language, however, little is known about musical enculturation in preschool children. In two experiments, we examined the development of enculturation to two aspects of Western pitch structure: key and harmony.

Young infants are already sensitive to some aspects of pitch structure, which suggests that they are either born with processing biases for particular musical features, or that they acquire these biases with little exposure to music. Interestingly, musical predispositions tend to involve features that are relatively universal across musical systems (Hannon & Trainor, 2007). For example, young infants prefer consonant to dissonant musical

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intervals (Trainor & Heinmiller, 1998; Trainor, Tsang & Cheung, 2002; Zentner & Kagan, 1998), including 2-day-old hearing infants of deaf parents (Masataka, 2006). Furthermore, infants more readily process melodies according a relative rather than an absolute pitch code, an ability that enables melody recognition across transposition (Plantinga & Trainor, 2005), and they more readily process scales with unequal-sized than equal-sized intervals (Trehub, Schellenberg & Kamenetsky, 1999). Thus, before enculturation is evident, infants are already sensitive to basic aspects of musical pitch.

Sensitivity to features that are specific to a musical system depends on experience with that musical system. Most musical systems use scales, but the particular notes and intervals used vary across cultures. Thus, just as infants learn the particular phonemes, words and syntactic rules that are specific to their native language, so too do they learn the particular scale, key, and harmonic structures of the music of their culture. This implicit knowledge is likely acquired using domain-general processes such as statistical learning. Indeed, research has shown that infants can extract statistical information from both syllable (Saffran, Aslin & Newport, 1996) and tone (e.g. Saffran, Johnson, Aslin & Newport, 1999) sequences.

The major scale is the most common scale on which Western musical pieces are based. This scale is composed of seven of the 12 possible pitch classes of the chromatic scale, which is created by dividing the octave into 12 equal semitone (6% pitch difference) intervals. A major scale consists of the intervals tone, tone, semitone, tone, tone, tone, semitone, where a tone equals two semitones. The scale can begin on any one of the 12 pitch classes and is named for its starting note. For example, the key of C major is based on the C major scale, which begins on the note 'C' and includes the notes C, D, E, F, G, A, and B. Knowledge of key membership involves understanding which notes belong to the scale on which a musical piece is based and which do not (for example, the note D-flat does not belong to the key of C major).

By contrast, harmony perception requires finer-grained knowledge of the hierarchical organization of notes and chords within a key. This knowledge includes implicitly understanding how typical chords are built and which notes and chords tend to follow others in a musical piece, as well as acquiring sensitivity to the relative frequency and stability of different notes and chords within a key. In Western music, chords can be built on any note of the scale by combining the starting note with the third and fifth notes above it; thus, a chord built on the first note of the C major scale (referred to as the tonic chord) would include the notes C, E, and G, whereas a chord built on the fifth note (referred to as the dominant chord) would include the notes G, B, and D.

Chord sequences follow probabilistic syntactic rules. For example, a phrase ending with a dominant chord followed by a tonic chord is perceived as sounding complete. The tonic chord is typically the most frequently occurring chord in a musical piece, and it is perceived as the most important and stable sounding (Krumhansl, 1990). Harmony perception therefore involves an understanding of the statistical regularities of different notes and chords within a key, as well as expectations for which notes and chords follow others. It is well known that even musically untrained Western adults are sensitive to both key membership and harmony (for reviews, see Bigand & Poulin-Charronnat, 2006; Krumhansl, 1990; Krumhansl & Cuddy, 2010), but the developmental acquisition of this implicit knowledge has been understudied.

Young infants do not appear to be sensitive to key membership or harmony. For example, infants of approximately 9 to 11 months of age perform equally well at detecting changes to musical stimuli that do or do not conform to Western pitch structure, whereas older children and adults show an advantage for Western stimuli (Trehub, Cohen, Thorpe & Morrongiello, 1986; Trehub *et al*., 1999). Furthermore, 8-month-olds detect out-of-key and in-key changes to a Western melody equally well, whereas adults are better at detecting out-of-key changes (Trainor & Trehub, 1992). There is evidence that with music training during infancy, some preliminary enculturation to musical pitch structure is evident by 12 months of age (Gerry, Unrau & Trainor, 2012; Trainor, Marie, Gerry, Whiskin & Unrau, 2012); however, the developmental trajectory for enculturation to key membership and harmony in the majority of children who do not take formal music classes remains unknown.

Research examining musical development in children has used three basic methodologies: first, asking for explicit judgments about musical passages that fit or do not fit Western key and harmony rules; second, examining processing biases (using implicit measures) for music that does or does not conform to Western pitch structure; and third, examining whether notes and chords that do or do not violate Western key and harmony rules elicit different electrophysiological brain responses. Explicit judgments are significant because they can indicate children's conscious, evaluative perceptions of music. Implicit tasks and electrophysiological measures are important because they can reveal implicit knowledge in individuals who cannot yet make evaluative decisions regarding how good or bad a note or chord sounds in a musical piece.

Studies on children's explicit knowledge of key membership and harmony have used Krumhansl's (1990) probe-tone technique whereby listeners rate how good or bad the last note or two (probe tones) of a melody or chord sequence sound across trials. The youngest children tested (6-year-olds) with this method demonstrated sensitivity to key membership and harmony by giving the highest ratings to notes that belonged to the tonic chord and by giving the lowest ratings to notes that fell outside of the key of the melody (e.g. Cuddy & Badertscher, 1987; Speer & Meeks, 1985), although there is also evidence that this sensitivity continues to develop beyond 6 years of age (Krumhansl & Keil, 1982). The probe-tone method shows that enculturated listeners can make explicit judgments about their musical knowledge, but rating scales are difficult to use with preschool children because they tend to choose the extreme ends of a scale regardless of the number of response options (e.g. Chambers & Johnston, 2002). Furthermore, the task usually requires participants to complete many trials, which is beyond the attentional limits of most young children.

To obtain explicit judgments without using rating scales, other studies have asked participants to make binary decisions about musical stimuli. For example, Corrigall and Trainor (2010) found that 4- to 5-year-old children judged a familiar song (i.e. *Twinkle Twinkle Little Star*) that ended correctly as sounding 'right' or 'good' significantly more often than when it ended outside of the key or outside of the most expected harmony. These results suggest that young children can demonstrate knowledge of the musical pitch structure of their culture in certain situations, such as when the musical passages are familiar, although it remains unknown whether this knowledge generalizes to unfamiliar Western musical passages. Nevertheless, the findings also suggest that preschoolers' explicit knowledge of musical structure can be assessed with a two-alternative forced choice method. In the present research, we implemented this type of task to examine children's sensitivity to key membership and harmony in unfamiliar but conventional Western musical sequences.

In the domain of implicit tasks, children's musical enculturation has been examined with change detection procedures. For example, Trehub *et al.* (1986) showed that 4- and 5-year-olds were better able to detect a semitone change in a Western melody than in a non-Western melody, suggesting that they had some knowledge of key membership. Similarly, Trainor and Trehub (1994) showed that 5-year-olds were better able to detect a changed note in a Western melody that went outside the key compared to a change that remained in the key, whereas 7-year-olds and adults further differentiated among in-key notes, detecting out-of-harmony changes better than changes that remained in-harmony. These results suggest that 5-year-olds are sensitive to key membership and that 7-year-olds have additionally acquired implicit knowledge of harmony. Using a different type of implicit task that has been used extensively with adults (e.g. Bigand & Pineau, 1997; Bigand, Poulin, Tillmann, Madurell & D'Adamo, 2003; Tillmann, Bigand & Pineau, 1998), Schellenberg, Bigand, Poulin-Charronnat, Garnier and Stevens (2005) found that 6- to 11-year-olds judged an unrelated aspect of the final chord in a sequence (e.g. whether it was played in a piano or trumpet timbre) faster when it was harmonically appropriate than when it was a less expected chord. These results suggest that children as young as 6 years of age automatically form harmonic expectations that influence their processing of music even when harmonic appropriateness is irrelevant to the task at hand. The advantage of implicit tasks is that they have the potential to reveal knowledge that might not otherwise be detected by explicit tasks. However, implicit tasks often require many trials, limiting their usefulness with young children. Furthermore, preschoolers are typically unable to do the speeded judgments required in reaction time tasks. Thus, these types of implicit tasks can be impractical for preschoolers.

Finally, another way to tap implicit knowledge is by recording electroencephalography (EEG) and analyzing event-related potential (ERP) responses to stimuli that do or do not violate key membership and harmony rules. In adults, violations to musical pitch structure in chordal stimuli elicit an early negativity (typically with a peak latency of 150 to 180 ms in adults) found in right anterior regions, termed the early right anterior negativity (ERAN; see Koelsch, 2009, for a review). The ERAN is thought to reflect syntactic processing and to rely on long-term musical syntactic knowledge, similarly to the early left anterior negativity (ELAN) that is elicited by syntactic violations in language (e.g. Friederici, 2002). The ERAN is larger in 11-year-old children who have taken music lessons compared to non-musician children (Jentschke & Koelsch, 2009), suggesting that it strengthens with further enculturation. Furthermore, the ERAN is present even when participants are not required to attend to the musical stimuli, making it an ideal component to study in young children. Research has shown that the ERAN can be elicited in response to strong violations to key structure (Koelsch, Grossmann, Gunter, Hahne, Schröger & Friederici, 2003) or to harmonic violations (Jentschke, Koelsch, Sallat & Friederici, 2008) in children as young as 5 years of age, suggesting that 5-year-olds have some sensitivity to both key membership and harmony. A later component, the N5, is also elicited in response to musical syntactic violations under certain conditions, but is thought to be less automatic and more subject to attentional focus than the ERAN (e.g. Koelsch, Gunter, Friederici & Schröger, 2000; Koelsch & Siebel, 2005; Loui, Grent-'t-Jong, Torpey & Woldorff, 2005). Importantly, both the ERAN and the N5 are sensitive to the degree of harmonic violation, with larger responses corresponding to stronger violations (e.g. Koelsch *et al.*, 2003; Koelsch *et al.*, 2000; Leino, Brattico, Tervaniemi & Vuust, 2007). Although there are several limitations to using ERPs with children, such as the need for a large number of trials and for children to remain fairly still, the fact that the ERAN can be elicited during passive listening makes this method promising for use with preschoolers. Thus, we also conducted an EEG experiment to examine sensitivity to key membership and harmony in preschoolers whose explicit judgments in the two-alternative forced choice task did not yet reveal any knowledge of Western musical pitch structure.

In the present research, our first goal was to design an engaging and age-appropriate behavioral task that would elicit explicit judgments that reflected children's knowledge of key membership and harmony in unfamiliar Western music. Our second goal was to examine implicit knowledge in young children whose explicit judgments did not yet reveal any evidence of enculturation to Western musical pitch structure. We also sought to examine these skills in single-line melodies and in chord progressions, because enculturation to musical pitch has not yet been compared across these two contexts in children. In Experiment 1, we asked 4- and 5-year-olds to make explicit binary judgments about unfamiliar music that did or did not fit Western musical pitch structure. In Experiment 2, we examined 4-year-olds' ERP responses to a subset of the same stimuli.

Experiment 1

Four- and 5-year-olds watched videos of puppets playing the piano and judged which of two puppets deserved a prize. On each trial, one puppet's song followed Western pitch structure and the other's violated either key structure (in two conditions) or harmony (in one condition). We measured children's tendency to award the prize to the puppet whose song conformed to key and harmony rules. Our design was an improvement on previous studies for two reasons: first, the addition of videos, puppets, and prizes made the task more engaging for children compared to just listening and making judgments to the musical stimuli and, second, this procedure required fewer trials than in previous studies, ensuring that children maintained attention throughout the experiment. Furthermore, we improved the generalizability of our results compared to previous studies by presenting a different sequence on each trial so that children's performance reflected general enculturation rather than specific learning of the particular experimental stimuli.

Method

Participants

We tested 72 4-year-olds (36 girls, 36 boys; M_{age} = 4.5 years, SD = 0.1 years) and 72 5-year-olds (36 girls, 36 boys; M_{age} = 5.5 years, SD = 0.1 years), with 12 girls and 12 boys of each age group assigned to one of three conditions. None of the children were enrolled in formal music lessons. An additional 22 children were tested but excluded from the analyses for the following reasons: enrolled in formal music training (n = 13), diagnosed with a developmental disorder (n = 5), failed to complete all testing (n = 2), or experimenter error (n = 2).

Stimuli

Musical sequences. We composed eight chord sequences, each consisting of five 4-note chords in root position, and eight 8-beat single-line melodies (each melody was two measures long in simple time) typical of Western musical structure. There were four versions of each chord sequence and each melody. The first was a *standard version* that followed the rules of Western harmony and always ended on the tonic note or chord. In the *atonal version*, each note or chord of the standard version was shifted up or down by a semitone, or left the same, such that the sequence as a whole did not belong to any particular key, while it maintained the same chord types (for chord sequences), or the same up/down pitch contour as the standard version (for melodies). The *unexpected key version* replicated the standard version except that the last note or chord ended one semitone higher than the tonic and thus went outside the key (a flat supertonic). The *unexpected harmony version* replicated the standard version except that the last note or chord ended on the subdominant, which is an in-key but less expected ending harmonically than the tonic. The subdominant and tonic chords are both major chords, ensuring that the results would reflect whether children expected the tonic chord in particular rather than simply any major chord. The standard, unexpected key, and unexpected harmony versions were composed such that

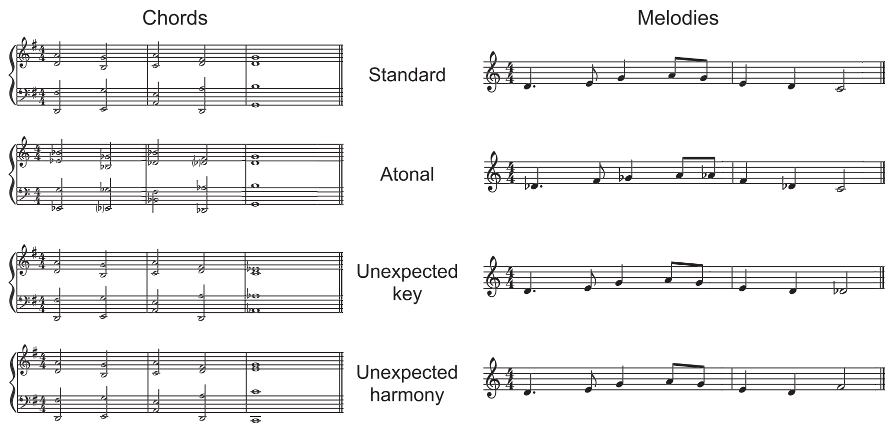

Figure 1 *Musical notation for all four versions (standard, atonal, unexpected key, unexpected harmony) of one example chord sequence and one example melody.*

neither the tonic nor the subdominant chord (in the chord sequences) or note (in the melody sequences) occurred in each sequence until the final chord or note. This was done to ensure that judgments of how these sequences ended could not be based on the frequency of occurrence of particular notes or chords in each sequence (i.e. sensory priming); rather, judgments would reflect children's knowledge of the rules of Western key membership and harmony (i.e. cognitive priming; see Bigand *et al*., 2003). Figure 1 shows the musical notation for all four versions of one example chord sequence and one example melody. One additional chord sequence and one additional melody were composed and used for practice trials. For these sequences, the deviant versions violated Western musical structure strongly by including dissonant chords (for chord sequences) or large jumps in pitch that also went outside the key (for melody sequences). Chord sequences were 6 seconds in length and melodies were 4 seconds in length. A music theorist confirmed that our standard sequences were properly composed such that they reflected Western musical structure. To ensure that enculturated Western listeners did indeed perceive the standard versions as sounding expected or correct, and deviant versions as sounding unexpected or incorrect, we first had adult listeners perform a longer version of the task. Thirty-six adults (20 females, 16 males) between the ages of 18 and 46 years (M_{age} = 21.9 years, SD = 5.4 years) listened to one standard and one deviant version each of all eight chord sequences and all eight melodies, and judged which version sounded better. Adults selected the standard version significantly above the expected chance level (0.5) across all deviant conditions (all ps < .01), confirming the appropriateness of our stimuli: chords/atonal, M = .92, SD = .16; melodies/atonal, M = .94, SD = .17; chords/unexpected key, M = .98, SD = .08; melodies/unexpected key, M = .89, SD = .23; chords/unexpected harmony, M = .80, SD = .32; melodies/unexpected harmony, M = .90, SD = .18.

Videos. Puppets were filmed pressing keys on a toy keyboard to the rhythm of each sequence. Each trial consisted of a standard and a deviant version of a chord sequence or melody, and different puppets played each version. Each puppet pair (e.g. a cow and a pig) was associated with one particular chord sequence and one particular melody. Videos were then edited and paired with the previously created audio files using Adobe Premiere, and exported to mp4 file formats. Because the audio files were added to the videos after recording, we were able to pair the same video clip with all four versions of its corresponding chord sequence or melody. This procedure enabled us to counterbalance the particular puppet in each pair that played the standard across children while keeping the videos constant. Videos lasted 9 seconds for chord sequences and 8 seconds for melodies, and all videos began with 2.5 seconds of silence and ended with silence.

Procedure

Each child sat at a small table in front of a 24-inch widescreen monitor and M-Audio Studiophile AV 40 speakers, which were both connected to a 3.4 GHz iMac using iTunes to play all videos. The experiment was framed as a puppet concert, in which children would give prizes to the puppets that played the best songs. On each trial, the child first watched videos of two puppets playing the piano: one played the standard version and the other played one of the three deviant versions. The experimenter then placed both of the puppets seen in the videos in front of the child and asked: 'Who gets the prize?' The child placed a ribbon on whichever puppet he or she deemed the winner. In keeping with our goal of maintaining children's attention throughout the experiment, we kept the number of trials to a minimum. Each individual child completed the chord and melody conditions (one practice trial and four test trials each) for one deviant type (atonal, unexpected key, or unexpected harmony); thus, each child completed a total of two practice trials and eight test trials. Whether children heard chords or melodies first was counterbalanced across children. For each child, the standard came first for half of the trials and second for the remaining half, and the puppet that played the standard was placed in front of the child on the left for half of the trials and on the right for the other half. Each particular puppet appeared only once to each individual child so that judgments could not be based on the puppet's past reliability (i.e. whether the puppet previously played the standard or deviant sequence), and every trial began in a new key so that children could not base their judgments on the frequency of a particular set of absolute pitches.

Each child additionally completed a forward digit span test between the two blocks of trials as a measure of short-term memory, and the Peabody Picture Vocabulary Test - 4th Edition (PPVT-4; Dunn & Dunn, 2007) after both blocks as a measure of receptive language ability. Because there are no published norms on children's digit span scores below the age of 6, we used their raw scores. Children's PPVT-4 scores were standardized according to age. Parents completed a questionnaire on their child's demographics, musical exposure, extracurricular activities, and basic health. Each child received a book or toy and certificate as appreciation for participating.

Results and discussion

The dependent measure was the proportion of trials on which children selected the puppet that played the standard version. Figure 2 shows the average for each age group (4-year-olds, 5-year-olds) for each song type (chords, melodies) and deviant condition (atonal, unexpected key, unexpected harmony). We first conducted a series of planned *t*-tests comparing children's performance to chance (0.5). As these were planned analyses, we did not correct for the number of *t*-tests performed. Four-year-olds performed at chance in every case: chords/atonal, $t(23) = 1.10$, $p = .29$; melodies/atonal, $t(23) = 1.23$, $p = .23$; chords/unexpected key, $t(23) = 1.30$, $p = .21$; melodies/unexpected key, $t(23) = 1.00$, $p = .33$; chords/unexpected harmony, $t(23) = .94$, $p = .36$; melodies/unexpected harmony, $t(23) = 1.34$, $p = .19$. By contrast, 5-year-olds selected the puppet that played the standard version significantly more often than predicted by chance in the atonal condition for both chords, $t(23) = 3.82$, $p < .01$, and melodies, $t(23) = 2.60$, $p = .02$, and in the unexpected key condition for both chords, $t(23) = 3.21$, $p < .01$, and melodies, $t(23) = 3.56$, $p < .01$, suggesting that these children had knowledge of key membership. Five-year-olds performed at chance, however, in the unexpected harmony condition for both chords, $t(23) = .85$, $p = .41$, and melodies, $t(23) = 1.57$, $p = .13$, suggesting that they are not yet able to demonstrate behavioral sensitivity to harmonic relationships within a given key.

To directly compare 4- and 5-year-olds' performance and to examine the possibility of sex differences, we conducted a $2 \times 2 \times 2 \times 3$ ANOVA with song type (chords, melodies) as the within-subjects factor and age group (4-year-olds, 5-year-olds), sex (girls, boys), and deviant condition (atonal, unexpected key, unexpected

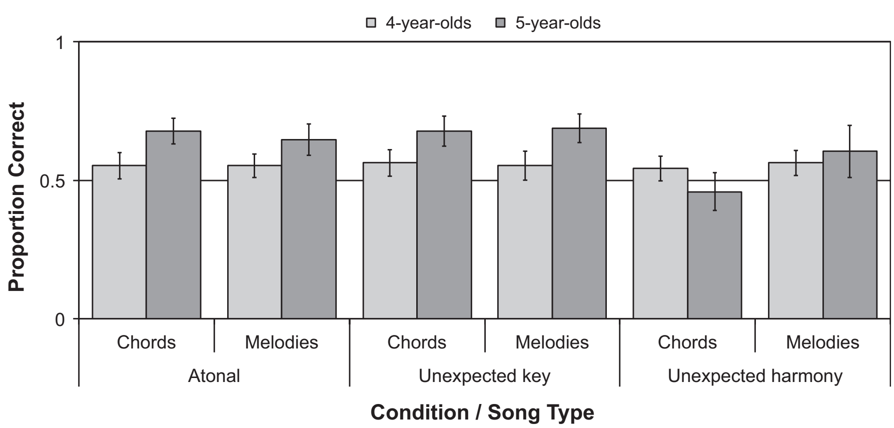

Figure 2 *Behavioral results from Experiment 1. The proportion of trials in which 4- and 5-year-old children chose the version that conformed to Western musical structure is shown for each condition. Error bars represent standard error.*

harmony) as between-subjects factors. There were significant main effects of age group, $F(1, 132) = 5.00$, $p = .03$, and sex, $F(1, 132) = 5.51$, $p = .02$; the main effect of condition approached significance, $F(2, 132) = 2.60$, $p = .08$, as did the age group by condition interaction, $F(2, 132) = 2.38$, $p = .10$, but no other effects were significant (all $ps > .10$). These results reflected the fact that 5-year-olds performed better than 4-year-olds, and that girls performed better than boys. Because the age group by condition interaction approached significance, we performed separate one-way ANOVAs for each condition with age group as a between-subjects factor on children's overall performance because we did not find any significant effects involving song type in the previous analysis. There was a significant effect of age group in the atonal condition, $F(1, 46) = 5.23$, $p = .03$, and in the unexpected key condition, $F(1, 46) = 4.25$, $p = .05$, but not in the unexpected harmony condition, $F(1, 46) = .24$, $p = .63$. These results reinforce the previous analyses comparing children's performance to chance. In summary, 5-year-olds outperformed 4-year-olds in the conditions that tested for knowledge of key membership (atonal and unexpected key conditions), with 4-year-olds performing at chance and 5-year-olds significantly above chance. On the other hand, the two groups performed similarly in the condition that tested for knowledge of harmony (unexpected harmony condition), with both groups performing at chance.

We conducted several further analyses. First, we asked whether the tendency for girls to perform better than boys was a general cognitive effect or whether it was specific to our music task. We conducted *t*-tests to compare girls' and boys' performance on the digit span task and the PPVT-4. Girls and boys did not differ on either the digit span task, $t(142) = .39$, $p = .70$, or on the PPVT-4, $t(142) = .31$, $p = .76$, suggesting that the girls' advantage was specific to the music task. It is possible that girls have more musical exposure than boys. Examination of the questionnaires completed by parents revealed that girls were more likely than boys to have taken baby or toddler music classes and/or dance classes (Mann-Whitney $U = 1184.5$, $p < .01$).

Table 1 *Correlational analyses in Experiment 1*

Variable	1.	2.	3.	4.
1. Age	–	.15†	.44**	−.11
2. Music performance		–	.12	.15†
3. Digit span			–	.32**
4. PPVT-4				–

†$p < .10$; **$p < .01$.

Next, we conducted correlational analyses to investigate whether the cognitive development in memory and language skills between 4 and 5 years of age might explain 5-year-olds' superior performance compared to 4-year-olds. To do this, we examined whether children's overall performance on our music task was correlated with their digit span and PPVT-4 scores. The results of these correlational analyses are reported in Table 1. Children's overall music performance averaged across song types was not correlated with their digit span, $r = .12$, $p = .17$, but the correlation between their music performance and their PPVT-4 scores approached significance, $r = .15$, $p = .08$. These results suggest that memory skills were not influencing children's performance on the music task, but that children's language skills might in part explain their musical perception skills. It is possible that children with more advanced language skills were better able to understand the task and thus performed better; alternatively, it is possible that receptive vocabulary acted as a estimate of overall intelligence and that more intelligent children tended to perform better on the music task.

Finally, to ensure that 4-year-olds' performance reflected a lack of behavioral sensitivity to key membership and harmony rather than a general difficulty with the task itself, we conducted an additional control condition. Eighteen 4-year-olds (five girls, 13 boys; $M_{age} = 4.5$ years, $SD = 0.1$ years) completed one practice trial and four test trials in which the puppets played the familiar song, *Twinkle Twinkle Little Star*. On each trial, the standard version was the single-line melody as written, whereas the deviant version was the same melody except that it ended on a note that was sixteen semitones lower than the standard ending and also went outside the key. Four-year-olds selected the standard version significantly more often than the deviant version, $M = .79$, $SD = .27$, $t(17) = 4.51$, $p < .001$. These results strongly suggest that 4-year-olds do not have difficulty with the task itself; rather, their poor performance in Experiment 1 is reflective of their lack of behavioral sensitivity to Western musical pitch structure in unfamiliar musical stimuli.

In Experiment 1, we assessed young children's explicit judgments of unfamiliar sequences that did or did not violate Western key membership or harmony. Using this engaging and age-appropriate but conservative test, we found that 5-year-olds were sensitive to key membership but not harmony, and that 4-year-olds did not demonstrate any knowledge of Western pitch structure in their explicit judgments. In Experiment 2, we examined whether event-related potentials might reveal partial musical knowledge in 4-year-olds.

Experiment 2

We recorded EEG while 4-year-olds watched a silent movie to keep them entertained, and listened to a subset of the stimuli from Experiment 1. We measured ERPs to the last note or chord of each sequence and compared the responses to standard, expected endings with responses to unexpected key or unexpected harmony endings. In particular, we examined whether children showed an ERAN or ERAN-like response, similar to what has been found in adults and older children.

Because no previous studies have examined whether the particular violations of interest here elicit ERAN and N5 in adults, we first conducted the EEG experiment with adults to ensure that the typical responses (an early negativity corresponding to the ERAN and late negativity corresponding to the N5) could be elicited using our stimuli. We found (1) an early negativity (ERAN) in both the chords/unexpected key and the melodies/unexpected key conditions, (2) a late negativity (N5) in both the chords/unexpected key and the chords/unexpected harmony conditions, and no significant components in the very subtle melodies/unexpected harmony condition (see Figures 3 and 4; Supplementary Methods and Results).

To our knowledge, this is the first ERP experiment in children that included both melody and chords conditions, and that tested musical syntactic knowledge using both unexpected key and unexpected harmony deviants. It is also the first to examine responses to subtle harmonic violations (i.e. the subdominant note or chord). Furthermore, although previous research has shown that an adult-like ERAN response can be elicited in 5-year-olds (Jentschke *et al.*, 2008; Koelsch *et al.*, 2003), to date no published research has examined ERP responses to musical syntactic violations in children as young as 4 years of age.

Method

Participants

Forty-six 4-year-olds (24 girls, 22 boys; M_{age} = 4.5 years, SD = 0.1 years) participated. All but two of these children completed two blocks (one chords, one melodies) of the same deviant condition. An additional two children completed both blocks but were excluded from one of these blocks for excessive artifacts in their EEG data. The final sample included 12 girls and 10 boys in the chords/unexpected key condition, 11 girls and 11 boys in the melodies/unexpected key condition, 12 girls and 9 boys in the chords/unexpected harmony condition, and 12 girls and 11 boys in the melodies/unexpected harmony condition. Most children had previously participated in Experiment 1 (n = 30), but whenever possible, we presented them with different sequences from the ones that they had heard previously. An additional eight children were recruited to participate but were excluded from both blocks of the final sample for the following reasons: unwilling to put or keep the EEG cap on (n = 2), excessive movement or artifacts in the EEG data (n = 5), enrolled in formal music training (n = 1).

Stimuli

We used a subset of the standard, unexpected key, and unexpected harmony versions of the same sequences from Experiment 1 (four chord sequences and four melodies), and transposed each to all 12 major keys. However, we sped up the tempo of these sequences such that each lasted 3.6 seconds in order to maximize the number of trials we could present in each 15-minute block.

Procedure

Children sat either next to their parent or on their parent's lap in a sound-attenuated room, facing a speaker and a monitor that were positioned approximately 1 meter away. An experimenter instructed children to be 'as quiet as a mouse' and 'as still as a statue' and silently reminded them of these instructions if they forgot during the experiment. Children watched a silent movie of their choice while the musical stimuli played from the speaker. Most children completed one block of chords and one block of melodies of the same deviant condition with a short break in between the blocks (see Participants section), and we counterbalanced the order of these blocks across children.

Each block included 120 trials of the standard and 120 trials of the deviant version of the same melody or chord sequence, transposed to all major keys and presented in a pseudo-random order such that no two consecutive trials could be presented in the same key. Stimuli were presented using E-prime version 1.2 software. After the experiment, children received a certificate and a book or toy as appreciation for participating.

EEG data recording and analysis

We recorded EEG with a Geodesic Sensor net and Electrical Geodesics Inc. Netstation 4.3.1 software at 124 or 128 scalp locations (depending on the net size that fit the child's head). Online, EEG was recorded at a sampling rate of 1000 Hz with a Cz reference, and

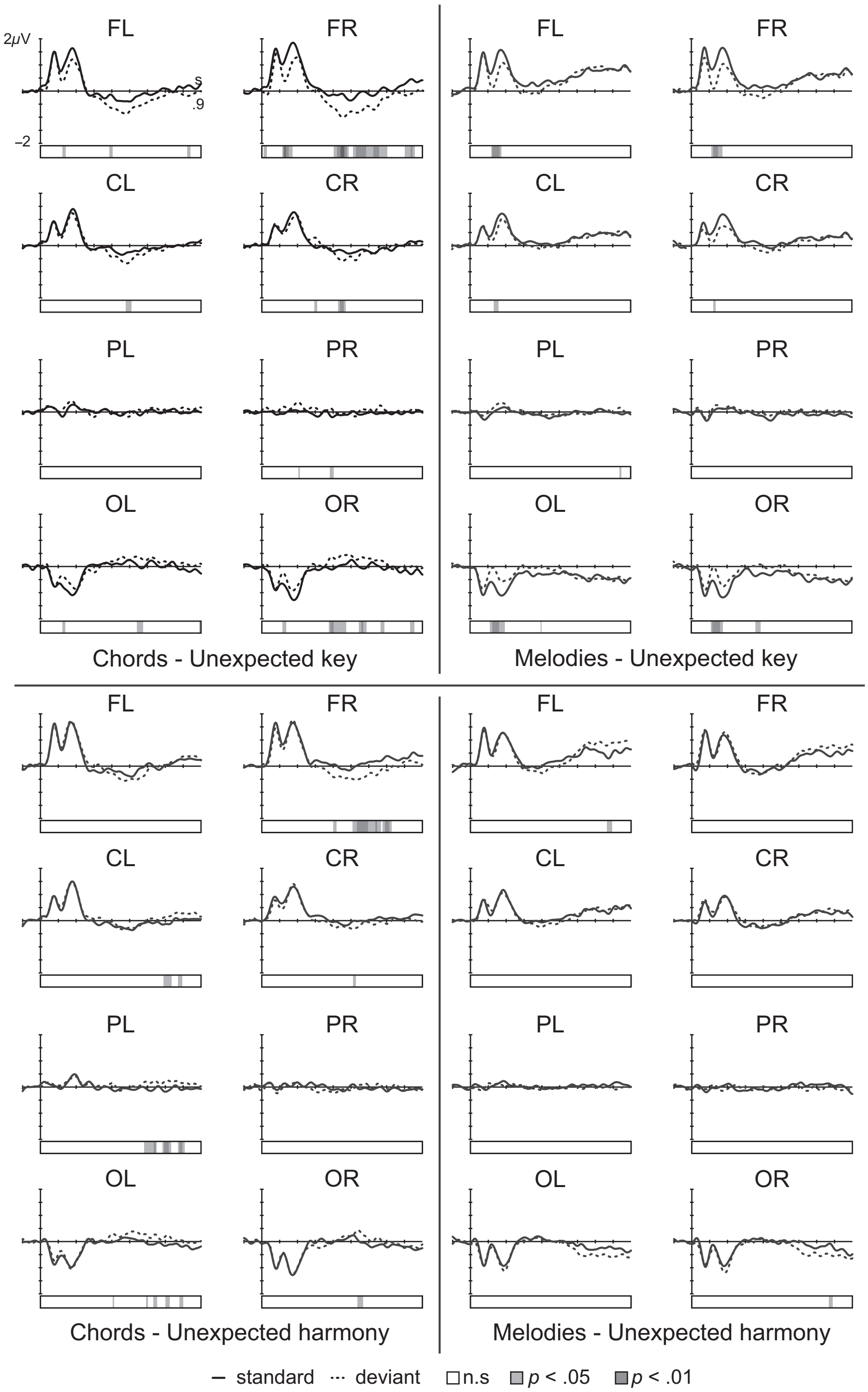

Figure 3 *Grand average waveforms of responses to standards (black lines) and deviants (dotted lines) in each condition and in each region in adults. Boxes underneath each waveform indicate the significance level of t-tests conducted on the difference between standard and deviant waves at each time point. The y-axis marks the onset of the last note or chord in each sequence.*

bandpass filtered between 0.1 and 400 Hz, keeping impedances below 50 kΩ. Offline, the data were filtered between 0.5 and 20 Hz, downsampled to 200 Hz, and then run through the artifact-blocking (AB) algorithm (see Fujioka, Mourad, He & Trainor, 2011) using a threshold of ±100 μV to reduce movement-related

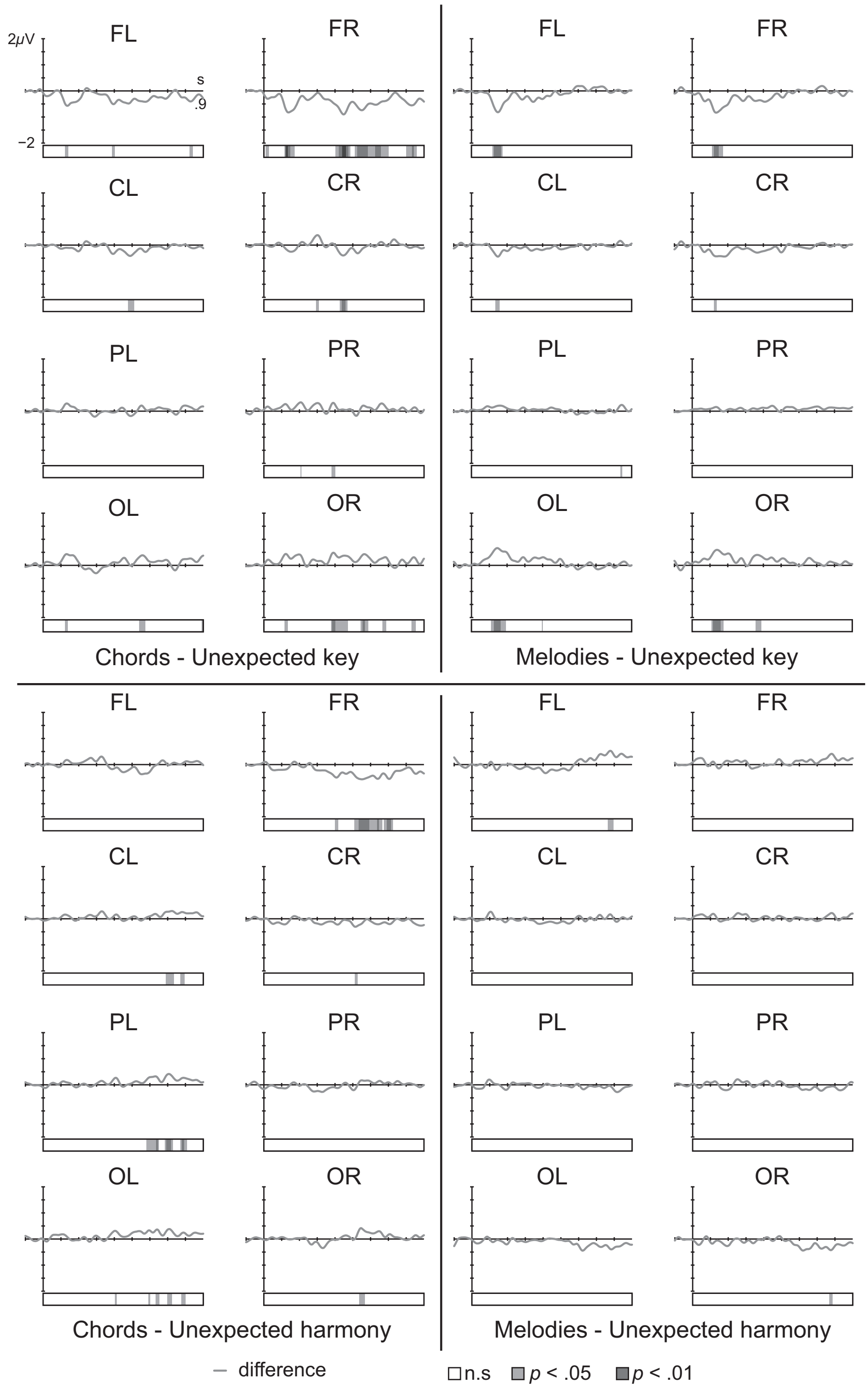

Figure 4 *Averaged difference waves (deviant – standard; grey lines) in each condition and in each region in adults. Boxes underneath each waveform indicate the significance level of t tests comparing difference waves to zero. The y-axis marks the onset of the last note or chord in each sequence.*

artifacts. Electrodes were then digitally re-referenced to a common average, and the data were segmented into 900 ms epochs with a baseline starting 100 ms before the onset of the final chord (chord sequences) or note (melodies) of each trial. For each electrode site, standard and deviant trials were averaged separately relative to the

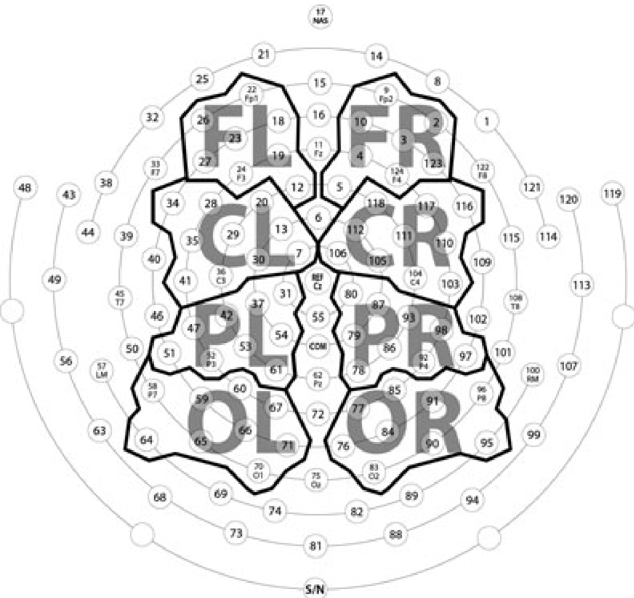

Figure 5 *Electrode groupings used in the analyses of Experiment 2 (FL = frontal left, FR = frontal right, CL = central left, CR = central right, PL = parietal left, PR = parietal right, OL = occipital left, OR = occipital right). Each region included between 8 and 10 electrode sites.*

100 ms baseline. For analysis, eight groups of electrodes were formed, averaging together the channels in each group that corresponded to frontal, central, parietal, and occipital regions of the scalp for each hemisphere (see Figure 5). We then created a difference wave for each participant in each condition at each scalp region by subtracting the standard waveform from the deviant waveform.

Results and discussion

Grand average standard and deviant waveforms in each condition are shown in Figure 6, and difference waves in Figure 7. Preliminary *t*-tests comparing standard and deviant waves across time revealed an early component (deviants more positive than standards) in both the chords/unexpected key and chords/unexpected harmony conditions. In addition, a late positive component was identified in the chords/unexpected harmony condition. A late positive component also appeared to be present in the chords/unexpected key condition, but was not significant by *t*-tests across time and therefore it was not analyzed further. These components were present in both the frontal and central regions and reversed polarity in the occipital regions (see Figure 8 for head maps of the grand average difference waves for the chords/unexpected key condition at 200 ms after the onset of the final chord, and for the chords/unexpected harmony condition at 240 ms and at 550 ms). No significant differences were observed for the melody conditions; thus, no further analyses were conducted.

The peaks of the early and late components in the grand average at frontal and central sites identified in the preliminary analyses were used to specify times windows ($\pm$50 ms around the peak of the grand average for the early component, $\pm$125 ms around the peak of the grand average for the late component) in which the average amplitudes of the difference waves were calculated and used as the dependent measures in the following analyses. The average amplitudes at occipital regions were reverse-signed (such that negative average amplitudes were transformed to have a positive average amplitude and vice versa) so that the magnitude of the component across scalp regions could be analyzed. Parietal regions were not included as no significant components were present. Greenhouse-Geisser corrections to degrees of freedom were used whenever appropriate. For each analysis (early and late components for each condition), within-subjects factors were hemisphere (left, right) and region (frontal, central, occipital), and the between-subjects factor was sex (girls, boys).

Key membership

In the chords/unexpected key condition, the time window of the early peak in the difference wave was 150 to 250 ms after the onset of the final chord. The ANOVA revealed no main effect of hemisphere, $F(1, 20) = 1.78$, $p = .20$, region, $F(2, 40) = 1.80$, $\varepsilon = .76$, $p_{adj} = .19$, or sex, $F(1, 20) = .30$, $p = .59$, and no significant interactions involving any of these factors, suggesting that the size of the early component was similar across hemispheres, regions, and sex of the participants. Because we did not find any main effects or interactions in the overall ANOVA, we then conducted a *t*-test on the average amplitude of the difference wave between 150 and 250 ms, averaged across the left and right frontal, central, and occipital regions and found that it was significantly different from zero, $t(21) = 4.31$, $p < .01$.

Thus, in contrast to the ERAN that has been found in children as young as 5 years (e.g. Jentschke *et al*., 2008; Koelsch *et al*., 2003), we found an early positivity in frontal regions in younger children with an average age of 4.5 years. These results suggest that young children have some sensitivity to key membership at the level of implicit processing because in-key chords elicited a pattern of brain activity that is different from out-of-key chords at an early latency. However, the fact that their response was an immature bilateral positivity in frontal scalp sites rather than an adult-like frontal negativity

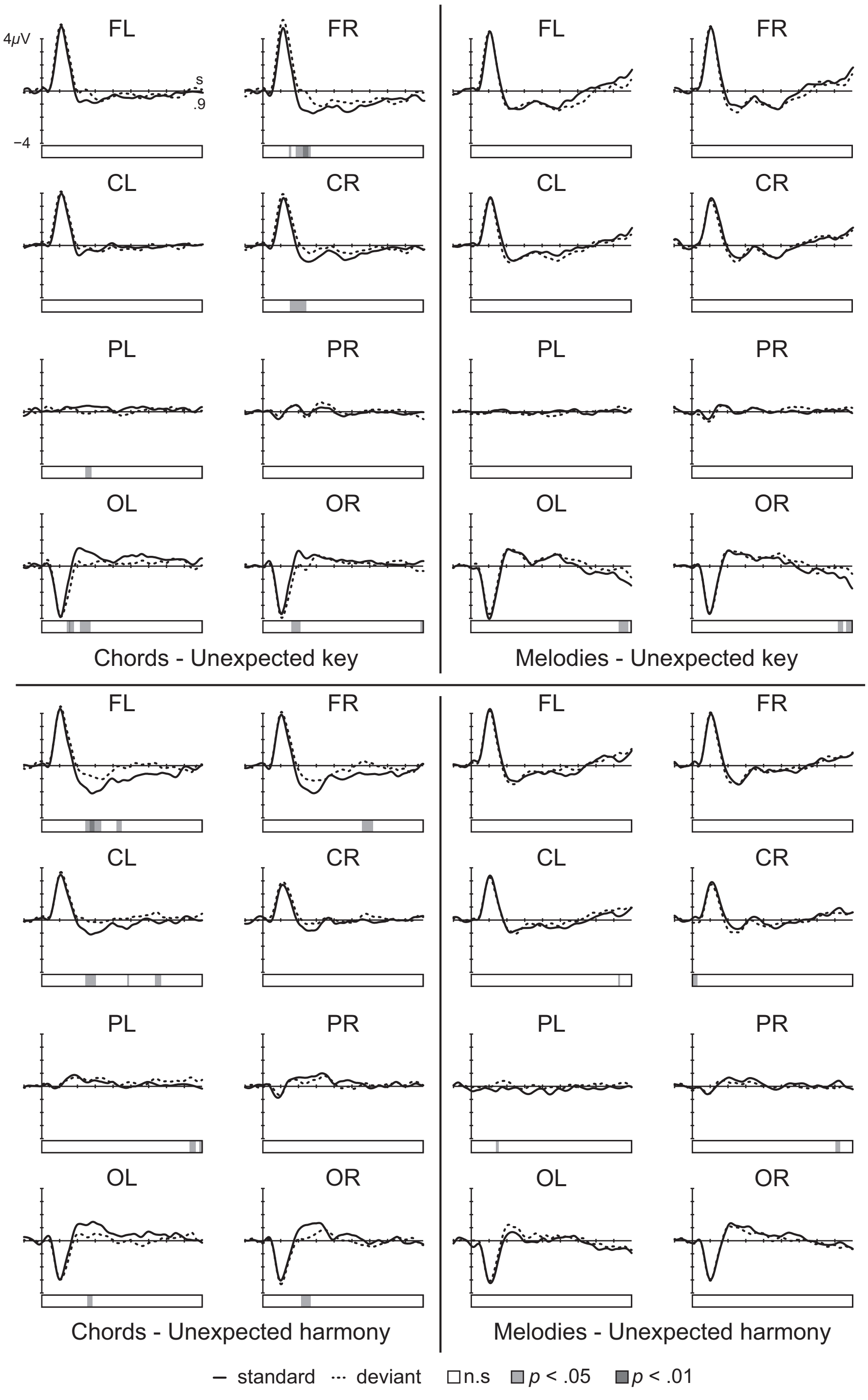

Figure 6 *Grand average waveforms of responses to standards (black lines) and deviants (dotted lines) in each condition and in each region in children from Experiment 2. Boxes underneath each waveform indicate the significance level of t-tests conducted on the difference between standard and deviant waves at each time point. The y-axis marks the onset of the last note or chord in each sequence.*

further supports the idea that this component may reflect knowledge that cannot yet be expressed behaviorally. Moreover, we did not find any significant components in the difference waves of the melodies/unexpected key condition, although a clear early negativity was present in adults' responses (see Figures 3, 4; Supplementary

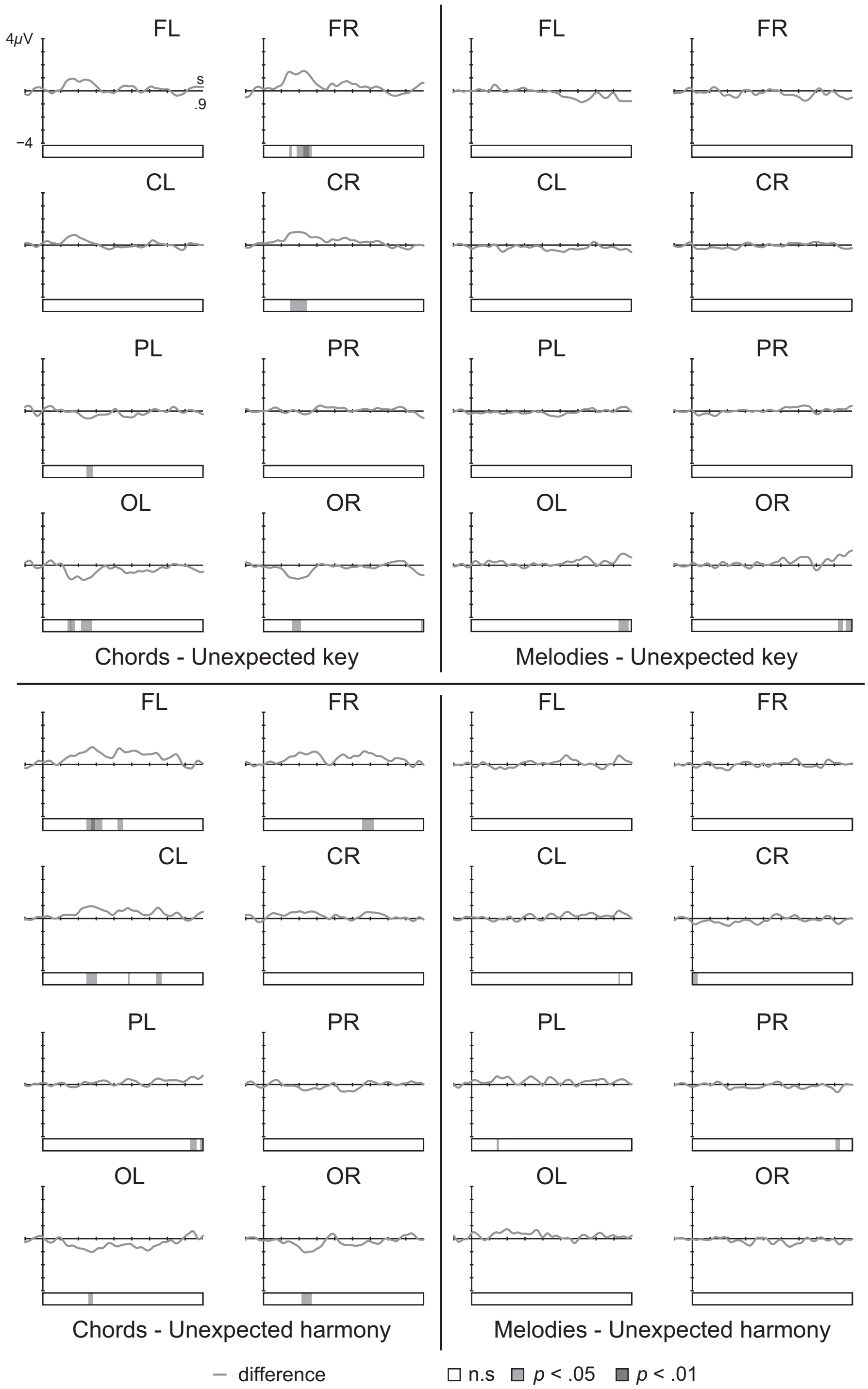

Figure 7 *Averaged difference waves (deviant – standard; grey lines) in each condition and in each region in children. Boxes underneath each waveform indicate the significance level of t-tests comparing difference waves to zero. The y-axis marks the onset of the last note or chord in each sequence.*

Methods and Results). Because components that are elicited by expected compared to unexpected notes in melodies can be quite small even in adults (e.g. Koelsch & Jentschke, 2010), it is perhaps unsurprising that we failed to identify any such components in young children. Chords contain rich harmonic information

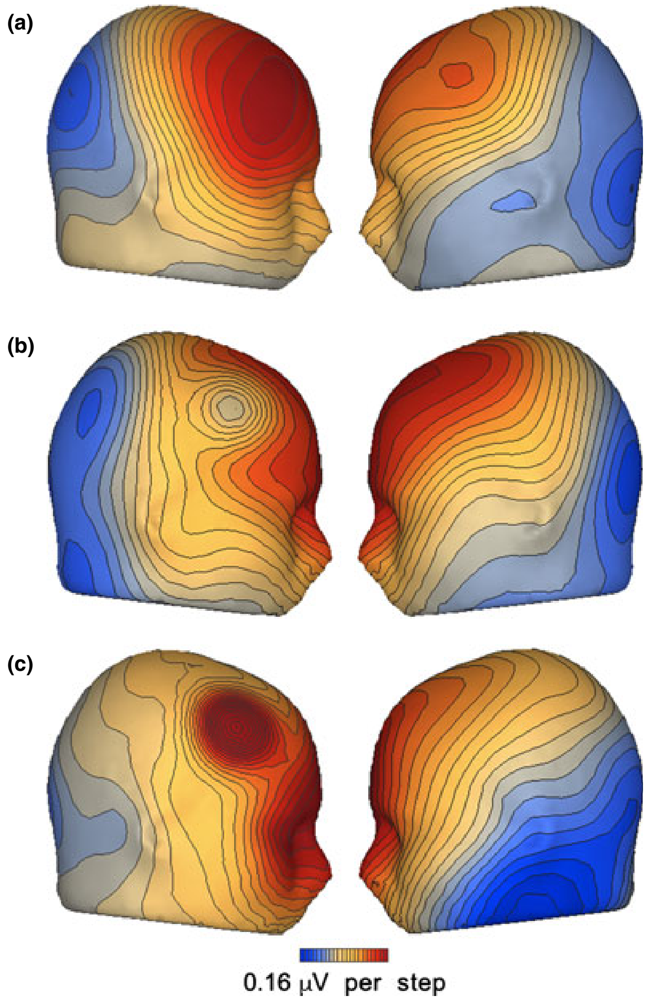

Figure 8 *Topographies of the difference wave in (a) the chords/unexpected key condition for the early component (at approximately 200 ms after the onset of the final chord), and the chords/unexpected harmony condition for (b) the early component (at approximately 240 ms) and (c) the late component (at approximately 550 ms). The red end of the scale indicates a positive voltage while the blue end of the scale indicates a negative voltage.*

because of the simultaneous combination of notes, whereas melodies contain less information and therefore fewer cues to key and harmony.

Harmony

In the chords/unexpected harmony condition, the early component was measured as the average amplitude of the difference wave between 190 and 290 ms. The ANOVA revealed no main effect of hemisphere, $F(1, 19) = .00$, $p = .95$, region, $F(2, 38) = .64$, $\varepsilon = .77$, $p_{adj} = .50$, or sex, $F(1, 19) = .70$, $p = .42$, and no significant interactions, but the average amplitude of the component across hemispheres and regions differed significantly from zero, $t(20) = 2.95$, $p < .01$. The late component was measured between 425 and 675 ms. Again there was no main effect of hemisphere, $F(1, 19) = .22$, $p = .65$, region, $F(2, 38) = 1.51$, $\varepsilon = .71$, $p_{adj} = .24$, or sex, $F(1, 19) = .62$, $p = .44$, and no significant interactions involving these factors. The *t*-test comparing the average amplitude of the difference wave between 425 and 675 ms across hemispheres and regions to zero approached significance, $t(20) = 1.92$, $p = .07$. Thus, similar to the chords/unexpected key condition, an early positivity was also elicited in the chords/unexpected harmony condition, as well as a trend for a late component. These results are perhaps surprising in light of the behavioral results of Experiment 1, in which even 5-year-olds did not demonstrate knowledge of within-key harmonic expectations. The ERP findings suggest that children begin accumulating knowledge pitch structure long before that knowledge is sophisticated enough to be expressed behaviorally. We could not identify any significant components in the melodies/unexpected harmony condition, but the same results were found with adults (see Figures 3, 4; Supplementary Methods and Results). As this condition contained only weak harmonic violations to simple melodies, the most subtle manipulation of the experiment, this result is perhaps not surprising.

General discussion

Our first goal was to examine the development of children's explicit evaluative judgments of sequences that did or did not conform to Western pitch structure. Our task was engaging and maintained children's attention, but it was also conservative because each trial included a different unfamiliar sequence, ensuring that children's responses reflected their abstract knowledge of key membership and harmony rather than specific knowledge of the particular sequences used in the experiment, as was the case in previous studies (e.g. Corrigall & Trainor, 2009, 2010; Cuddy & Badertscher, 1987; Krumhansl & Keil, 1982; Trainor & Trehub, 1994; Trehub *et al.*, 1986). Five-year-olds were sensitive to key membership as they chose to award prize ribbons to puppets that played standard Western sequences significantly more often than puppets that played atonal sequences or sequences that ended in an unexpected key. However, whether or not a sequence ended in an expected harmony did not affect 5-year-olds' awarding of prize ribbons, which suggests that they were not yet sensitivity to harmony. By contrast, 4-year-olds did not demonstrate knowledge of Western pitch structure through explicit judgments, as they awarded prize ribbons equally to puppets that played standard compared to deviant sequences. These results suggest that children's knowledge of key membership is sophisticated enough to be expressed through evaluative judgments by approximately 5 years of age.

These findings fit with previous research suggesting that children acquire sensitivity to key membership before harmony (e.g. Corrigall & Trainor, 2009, 2010; Trainor & Trehub, 1994), and extend it in two ways. First, there were no differences in performance for chordal compared to melodic sequences, which implies that there is a similar developmental trajectory for sensitivity to Western pitch structure in these two contexts. Second, 5-year-olds were sensitive to key membership in both the atonal and the unexpected key conditions whereas 4-year-olds were not. These results indicate that once children can demonstrate knowledge of key membership through explicit judgments, their knowledge can generalize across different contexts of key membership violation. In other words, 5-year-olds appear to be just as good at identifying one wrong chord or note in a Western sequence as they are at recognizing that an entire passage does not conform to Western key membership rules. Together with previous research, the findings suggest that children have a fairly stable representation of key membership by approximately 5 years of age (e.g. Corrigall & Trainor, 2009, 2010; Jentschke *et al*., 2008; Koelsch *et al*., 2003; Trainor & Trehub, 1994; Trehub *et al*., 1986), but that a stable representation of harmony may not be in place until 6 or 7 years of age (e.g. Cuddy & Badertscher, 1987; Schellenberg *et al*., 2005; Trainor & Trehub, 1994), or even later (Costa-Giomi, 2003; Krumhansl & Keil, 1982).

Sensitivity to key membership and harmony likely arises through the accumulation of passive exposure to Western music. Children may then come to internalize the statistical regularities of the note and chord patterns that form the basis of key membership and harmony rules. However, general cognitive development might also contribute to the acquisition of musical knowledge itself, as well as to children's ability to express this knowledge. Our failure to find a correlation between performance on the music task and short-term memory in Experiment 1 suggests that children's performance on the music task was not driven by their memory skills. The near-significant correlation between performance on the music task and receptive vocabulary, however, suggests that children's understanding of the task or even general intelligence may contribute to their music task performance. On the other hand, we also obtained suggestive evidence that experience with music was a better predictor of musical enculturation than general cognitive skills: although girls and boys performed equally well on the general cognitive tasks, girls tended to outperform boys on the music tasks. Because girls were also more likely to have participated in early music or dance classes, our results point to the importance of everyday experience in acquiring knowledge of musical pitch structure. Furthermore, there is evidence that formal music training accelerates enculturation to Western pitch structure in both infants and children (Corrigall & Trainor, 2009; Gerry *et al*., 2012; Trainor *et al*., 2012), presumably because children in music lessons acquire more exposure to music than children not in lessons. Although these observations and correlations are suggestive of the role that experience plays in musical enculturation, further research is needed to confirm its importance. One issue that arises is the difficulty in quantifying how much music children are exposed to. It may be easy to estimate how often one deliberately listens to music on CDs, portable music players, and the radio, but music is also present in shopping malls, in schools and daycares, on television, and in movies, for example. A challenge for future research will be to accurately quantify children's amount of exposure to music and to examine whether this experience best explains individual differences in sensitivity to key membership and harmony.

Our second goal was to examine implicit knowledge of key membership and harmony in 4-year-old children who did not yet demonstrate this knowledge behaviorally. Children showed a positive ERP component in frontal and central regions between approximately 150 and 250 ms after the onset of the final chord in the chords/unexpected key condition, and between 190 and 290 ms as well as between 425 and 675 ms after the onset of the final chord in the chords/unexpected harmony condition. These results stand in contrast to previous studies with older children and adults that have found negative components (i.e. the ERAN and the N5) in response to similar stimuli (e.g. Koelsch *et al*., 2000; Koelsch, Gunter, Schröger, Tervaniemi, Sammler & Friederici, 2001; see Koelsch, 2009, for a review), and to our own results with adults (see Figures 3, 4; Supplementary Methods and Results). However, the positive components found in the current study were of a similar latency and were present in the same scalp regions as in previous ERAN studies with older children (e.g. Jentschke *et al*., 2008; Koelsch *et al*., 2003). Other auditory ERP components that appear as frontal negativities in adults also manifest as positivities in young children and infants (e.g. He, Hotson & Trainor, 2009; Tew, Fujioka, He & Trainor, 2009; Trainor, McFadden, Hodgson, Darragh, Barlow, Matsos & Sonnadara, 2003). We therefore suggest that the positive components that we obtained represent an immature ERAN-type response to a musical syntactic violation that emerges in development before behavioral sensitivity to these violations.

Our findings strongly suggest that the discrepancy in 4-year-olds' behavioral responses in Experiment 1 and their ERP responses in Experiment 2 stemmed from the nature of their musical representations rather than a more general difficulty or lack of engagement with the behavioral task. First, short-term memory was not correlated with performance on the music task in Experiment 1, which suggests that the task was not overly demanding on memory capacity. Second, we observed that 4-year-olds were very attentive in the behavioral music task. Third and most importantly, 4-year-olds performed well above chance (on average, 79% correct) in an additional control condition using familiar stimuli and a very strong violation. Together, these results imply that the behavioral task was both engaging and appropriate (i.e. not too difficult) for 4-year-olds, but that they lack explicit behavioral sensitivity to Western pitch structure. By contrast, the presence of the significant immature frontally positive ERP response suggests that at least a primitive representation of key membership and harmonic structure exists at age 4.

In sum, we found that by 5 years, children have a fairly robust and sophisticated understanding of key membership because they were able to make explicit judgments about the appropriateness of stimuli that did or did not violate Western key membership rules. However, 5-year-olds could not make these same judgments for stimuli that did or did not violate Western harmony rules, suggesting that harmony perception takes longer to develop. By contrast, although 4-year-olds did not demonstrate behavioral knowledge of key membership or harmony, their brain responses to chord sequences suggested that they have an immature implicit cortical representation of both key membership and harmony. Overall, our findings suggest that there is a long developmental trajectory for enculturation to Western pitch structure, and that children may have implicit knowledge of this structure long before they can express their knowledge behaviorally. Future research should pinpoint the youngest age at which sensitivity to key membership and harmony can be observed in order to better understand the development and emergence of enculturation to musical pitch.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Supplementary Methods and Results.