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Musical Training Influences Linguistic Abilities in 8-Year-Old Children: More Evidence for Brain Plasticity

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We conducted a longitudinal study with 32 nonmusician children over 9 months to determine 1) whether functional differences between musician and nonmusician children reflect specific predispositions for music or result from musical training and 2) whether musical training improves nonmusical brain functions such as reading and linguistic pitch processing. Event-related brain potentials were recorded while 8-year-old children performed tasks designed to test the hypothesis that musical training improves pitch processing not only in music but also in speech. Following the first testing sessions nonmusician children were pseudorandomly assigned to music or to painting training for 6 months and were tested again after training using the same tests. After musical (but not painting) training, children showed enhanced reading and pitch discrimination abilities in speech. Remarkably, 6 months of musical training thus suffices to significantly improve behavior and to influence the development of neural processes as reflected in specific pattern of brain waves. These results reveal positive transfer from music to speech and highlight the influence of musical training. Finally, they demonstrate brain plasticity in showing that relatively short periods of training have strong consequences on the functional organization of the children's brain.

Keywords: event-related potentials, musical training, neuropsychological tests, pitch processing, transfer of training

Introduction

There is growing evidence that musical expertise has profound consequences on the anatomo-functional organization of the human brain and the musician brain is consequently recognized as a good model of brain plasticity (Schlaug 2001; Münte et al. 2002; Pantev et al. 2003; Gaab et al. 2006). However, to date, only a few experiments have used brain imaging methods to examine the effects of musical expertise in children (Trainor et al. 1999, 2003; Koelsch et al. 2003, 2005; Shahin et al. 2004; Norton et al. 2005; Schlaug et al. 2005; Fujioka et al. 2006; Magne et al. 2006). Using functional magnetic resonance imaging (fMRI), Koelsch et al. (2005) have shown that musical expertise is correlated with increased activation in the right inferior fronto-lateral cortex and anterior part of the superior temporal gyrus. Reporting the preliminary results of on-going studies, Schlaug et al. (2005) found that children with 4 years of musical training had significantly more gray matter volume in several brain regions including the sensorimotor cortex and larger activation in the superior temporal gyrus than control children. Using the event-related potentials (ERPs) method, results have shown that the amplitude of early (P1, N1, and P2; Shahin et al. 2004) and late (P3; Trainor et al. 1999) auditory evoked potentials is influenced by musical expertise. The effect of musical expertise can therefore be seen throughout the course of development from early childhood to adulthood.

One question that remains to be answered, however, is whether the effects of musical expertise result from intensive musical practice or from specific predispositions for music. Several arguments favor the former view. First, anatomo-functional differences linked to musical expertise are typically correlated with the age of onset of musical training (Elbert et al. 1995; Schlaug et al. 1995; Schlaug 2001; Amunts et al. 1997; Jancke et al. 1997, 2000; Lotze et al. 2003). For instance, Trainor et al. (1999) have shown positive correlations between the age of onset of musical training and the amplitude of the P3 component. Second, differences are directly linked to the type of musical practice (Elbert et al. 1995; Pantev et al. 1998, 2001; Nager et al. 2003; Trainor et al. 2003). For instance, Pantev et al. have shown that magnetic evoked responses to piano sounds are larger in pianists than in nonmusicians (Pantev et al. 1998), whereas those evoked by trumpet sounds are larger in trumpet players than in pianists (Pantev et al. 2001). Third, the amount of musical practice is correlated with the level of musical expertise and with increased gray matter volume in several brain regions (Schneider et al. 2002; Gaser and Schlaug 2003). Fourth, short-term musical training produces effects similar to those found with long-term musical training (Bangert et al. 2001, 2006; Pascual-Leone 2001; Haueisen and Knosche 2001; Tremblay et al. 2001; Tremblay and Kraus 2002; Shahin et al. 2003, 2004; Bosnyak et al. 2004). Finally, recent MRI and fMRI results (Norton et al. 2005) showed no differences between children who were starting musical training and children who were not planning to take music lessons. It is, therefore, unlikely that specific predispositions led children to start music training.

Although these different arguments clearly highlight brain plasticity and the influence of musical training, they are most often based on correlational studies. In an attempt to go one step further and to demonstrate the causal relationship between musical training and musical expertise, we used a longitudinal approach with children. Very recently, Fujioka et al. (2006) have used such an approach with 4- to 6-year-old children tested 4 times over a year using the magnetoencephalography (MEG) method. They found that a magnetic component, the N250m, elicited by violin tones was enhanced in musically trained as compared to untrained children. However, because several factors were not controlled in this experiment, the authors concluded that preexisting differences between children, as well as differences in cognitive stimulation and motivation between groups, might account for this finding.

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In order to complement the findings of Fujioka et al. (2006), we conducted a longitudinal study with 8-year-old Portuguese nonmusician children. We ensured that children in the control group had an equally interesting training (painting) as in the music group and that there were no differences between children before training (pseudorandom assignment to the music or painting groups).

Previous results of our group using the ERPs method have shown that discrimination of small pitch variations (i.e., weak incongruities) at the end of short musical phrases is higher, and the amplitude of the N300 component of the ERPs is larger, in 8-year-old musician children with 4 years of musical training than in nonmusician children (Magne et al. 2006). Based on these results, the first aim of the present experiment was to determine whether training children with music will enhance the discrimination of weak incongruities in music and whether this enhancement will be associated with increased amplitude of the N300 component.

The second aim of the present experiment was to further examine transfer effects between music and language. Behavioral studies have provided mixed evidence of positive transfer effects between music and other perceptive and cognitive abilities. In a seminal paper, Gardiner et al. (1996) have shown that 5- to 7-year-old children who had art training (both music and painting) for 7 months performed better than controls in mathematics but not in reading. However, as children followed 2 types of training, it remained difficult to tease apart the specific effects of musical training. Moreover, results of a meta-analysis more recently published by Vaughn (2000) only show weak effects of musical training on mathematics (see also Costa-Giomi 2004). By contrast, a meta-analysis conducted by Bultzlaff (2000) revealed positive correlations between musical training and reading abilities. Music training has also been shown to influence spatio-temporal abilities (Costa-Giomi 1999; Hetland 2000), speech prosody (Thompson et al. 2004), verbal memory (Chan et al. 1998; Kilgour et al. 2000; Ho et al. 2003), second language phonological proficiency (Slevc and Miyake 2006) and general intelligence (Schellenberg 2004).

As pointed out by Schellenberg (2001), however, several factors (such as between-group differences, motivation, cognitive stimulation) were often not controlled in these experiments. Moreover, only a few studies (Chan et al. 1998; Kilgour et al. 2000; Ho et al. 2003; Schellenberg 2004; Thompson et al. 2004) aimed at specifying why music should enhance perceptual and cognitive abilities not directly linked to music. In our previous studies with adults (Schön et al. 2004) and children (Magne et al. 2006), we reasoned that if pitch, the perceptual attribute that corresponds to sound frequency, is an important acoustic parameter for both music and speech perception, increased efficiency in pitch processing due to musical expertise should improve pitch perception in speech. Results were in line with this hypothesis: children with 4 years of musical training detected small pitch variations (i.e., weak incongruities) in speech better than nonmusicians. At the neurophysiological level, these weak incongruities elicited larger positive components than the congruous speech control condition in musicians but no differences were found in nonmusician children. By contrast, large pitch variations (i.e., strong incongruities) in speech elicited similar ERP effects in both musician and nonmusician children, albeit with a shorter latency in the former group. Taken together, these results provide evidence for positive transfer effects between music and speech perception. Of most interest here is to determine whether training children with music will enhance the discrimination of weak incongruities in speech and whether this enhancement will be associated with increased amplitude of the positive components as previously found in musician children (Magne et al. 2006).

To summarize, we hypothesized that compared to painting training: 1) Musical training should improve the discrimination of weak incongruity in music and this improvement should be associated with an increase in the amplitude of the N300 component to weak incongruities and 2) Musical training should also improve the discrimination of weak incongruity in speech and this improvement should be reflected by increased amplitude of the positive components to weak incongruities.

In a previous attempt to test for the effects of musical training, we found that 8 weeks of musical training had no effects except to reduce the amplitude of the positivity to strong incongruities in speech (Moreno and Besson 2006). Because such large pitch deviations are easy to detect, this amplitude reduction was interpreted as reflecting the automation of pitch processing with musical training and the smaller size/greater efficiency of the neural networks necessary to perform the task (Batty and Taylor 2002; Jancke 2002). Based upon this result, and in contrast to weak incongruities, we therefore expected strong incongruities in speech to be associated with a reduced positivity in musically trained children compared to children in the painting group.

Finally, we further examined the influence of musical training on more general abilities such as reading (Bultzlaff 2000), verbal memory (Ho et al. 2003; Fujioka et al. 2006) and general intelligence (Schellenberg 2004). To this end we used standardized neuropsychological assessments (Wechsler Intelligence Scale for Children [WISC-III]) and specific Portuguese reading tests.

Methods

Participants

A total of 37 nonmusician children from 2 elementary schools in Aveiro (Northern Portugal) were enrolled in these experiments. Five children were excluded from final analysis either because they moved during the academic year (2) or because of too many artifacts in the electrophysiological recordings (3). The remaining 32 children were all attending the third grade (mean age: 101.1 months, SD = 4.3 in the music group and 98.8 months, SD = 4.7 in the painting group, $t(15) = 1.45$, $P > 0.17$). All had normal hearing, were right-handed and native speakers of Portuguese. All children also had similar middle socioeconomic backgrounds (as determined from the profession of the parents) and none of the children, and none of their parents, had formal training in music or painting. This was determined from a detailed questionnaire that parents were asked to fill in prior to the experiment. Most importantly, children were pseudorandomly assigned to musical training or to painting training (control group) to ensure that there were no prior-to-training differences between groups on the standardized and cognitive tests (WISC-III, verbal working memory and reading tests) or on the pitch discrimination tasks. The final 2 groups comprised 16 children each with 7 and 6 girls in the music and painting groups, respectively. Consent from local school authorities and from children's parents was granted before the beginning of data collection. (Prior to the start of the experiment, parents were informed in details about the procedure and about music and painting training. Both types of training were described as challenging, interesting and rewarding experiences for their children. Thus, none of the parents complained that their children followed one type of training and not

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the other. Rather they were pleased for their children to be given free music and painting lessons. Shortly after the start of training, children in the painting group went to an art exhibition and children in the music group went to a concert. Finally, at the end of training, the first group displayed their artwork at a school exhibition, and the second performed a concert at school. Thus, we did our best to ensure that children were as happy in both groups.) Children were given gifts at the end of Phases 1 and 3 (see below) to thank them for their participation and to maintain their motivation.

Design and Procedure

The experiment comprised 3 phases.

Phase 1 (3 weeks)

Children were tested individually in a quiet room of their school in 2 sessions (neuropsychological assessments and pitch discrimination tasks) that lasted for 2 h each and that were separated by 4 or 5 days. The results served as the basis for the pseudorandom assignment of children to the music or painting groups and as a baseline to evaluate the impact of the training programs. Testing all children individually required 3 weeks.

In the neuropsychological assessment session, children were tested using the WISC-III (Wechsler 2003 for the Portuguese adaptation) to compute an index of general intelligence (IQ). The IQ full scale was administered (10 subtests): 5 subtests to compute Verbal IQ scores (Information, Similarities, Arithmetic, Vocabulary, and Comprehension) and 5 subtests to compute Performance IQ (Picture Completion, Coding, Picture Arrangement, Block Design, and Object Assembly). Additionally, the Digit Span subtest was also administered to measure verbal short-term memory (direct order recall) and working memory (reverse order recall).

Reading skills were assessed by manipulating the complexity of print-to-sound correspondences(subset of stimuli from a newly developed Portuguese European reading battery, Sucena and Castro, in press). A total of 48 words (2- to- 4 syllables) were used with 24 words with simple and consistent one-to-one grapheme-to-phoneme correspondence (e.g., <bota>, *boot*), 12 words with complex but consistent mappings (e.g., 2-to-1 grapheme-to-phoneme correspondences, <mi**lh**o>, *corn*) and 12 words with complex and inconsistent mapping (i.e., the pronunciation cannot be derived by rules; e.g. <nexo>, *sense*). Children were seated in front of a laptop computer (Fujitsu Lifebook C Series) and were asked to read aloud, as accurately and as fast as possible, the words presented on the screen. Two blocks of 24 words each were presented (with 12 words in the Simple condition; 6 words in the Consistent condition and 6 words in the Inconsistent condition in each block). Responses were scored on-line by one experimenter and were recorded for off-line checking by another experimenter.

The WISC-III and reading tasks were always administered in this order to each child individually. Presentation of the stimuli and recording of the responses was controlled by the Cognitive Workshop program (courtesy of Philip Seymour, University of Dundee).

In the pitch discrimination session, 90 melodies and 90 Portuguese sentences were presented using the Presentation software (Neurobehavioral Systems, Albany, CA). The musical stimuli were selected from Schön et al. (2004). Half of the melodies belong to the international Western repertoire of children's music (see Fig. 1*A*) and we ensured that they were familiar to Portuguese children. The other half was composed by a professional musician. Tunes were converted into MIDI files using the synthetic sound of a piano (KORG XDR5). Sentences were selected from Marques et al. (2007) and were taken from children's books (e.g., "A Ana tinha junto da janela a flor azul colhida no pinhal," *Anne had by the window the flower from the pinewood,* see Fig. 1*B*). Sentences were spoken at a normal speech rate by a native Portuguese female speaker and were recorded in a soundproof booth on a G4 Macintosh computer at 48 kHz sampling rate using ProTools LE (Version 5.1.1, Digidesign Software, Daly City, CA). The mean duration of the melodies was 9.87 ± 2.42 s and of the final note 0.94 ± 0.21 s. The mean duration of the sentences was 3.26 ± 0.81 s and of the final word 0.52 ± 0.08 s.

Based upon results of pretests with both adults and children, the F0 of the final word was increased by using the software Praat (Version 4.1.15, Boersma and Weenink 2004) by 35% for the weak incongruity and by 120% for the strong incongruity (without changing the original pitch contour of the word). In the musical materials, the pitch of the last note was increased by 1/5 of a tone and by ½ tone for the weak and strong incongruities, respectively. Children were asked to decide, by pressing one out of 2 response buttons, whether the last word or note seemed normal or strange (i.e., something was wrong) and we analyzed both the percentage of correct responses and the ERPs to the final words/notes.

The experiment comprised an equal number of sentences/melodies (30) in each experimental condition (congruous, weak or strong incongruities) that were divided into 9 blocks of trials, with 6 blocks of 15 melodies and 3 blocks of 30 sentences (fewer melodies than sentences were presented within a block because melodies were of longer duration than sentences). In order to maintain attention and motivation throughout the experiment, 2 blocks of music trials alternated with one block of language trials. Within each block, an equal number of stimuli from each condition were presented in a pseudorandom order. Three lists of 90 sentences/90 melodies were used so that each sentence/melody was presented in each of the 3 conditions across children. The hand of response, the tasks (music or speech pitch discrimination) and block order within a task were counterbalanced across children. Practice blocks of 9 sentences or melodies were used to familiarize the children with the tasks and stimuli.

Phase 2 (24 weeks, excluding holidays)

Children participated in music or painting training for 24 weeks, twice a week for 75 min. Four teachers professionally trained in music or painting were specifically hired for this project and were assigned a subgroup of children (music: 10 and 8 children, respectively, and painting: 11 and 8 children, respectively).

Musical training was based on a combination of Kodály, Orff, and Wuytack methodologies (Wuytack and Palheiros 1995; www.kodaly.org.au) and included training on rhythm, melody, harmony and timbre. (Music training was based on the following aspects: *Rhythm*—children were trained to produce and improvise rhythms in different tempi and

Figure 1. Example of stimuli used in the music (*A*) and speech (*B*) pitch discrimination tasks "A Ana tinha junto da janela a flor azul colhida no pinhal," *Anne had by the window the flower from the pinewood*). The pitch of the final note/word was correct or parametrically manipulated so as to be weakly (1/5 of a tone or 35% F0 increase) or strongly incongruous (1/2 of a tone or 120% F0 increase).

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meters; *Melody*—exercises comprised the production and improvisation of melodies as well as inner audition. Children were taught to classify pitch contour and intervals [e.g., going up and down; low, middle and high tones; relative music reading]; *Harmony*—children were listening to harmonic progressions like I–IV–V–I, I–V–IV–I, or I–IV–V–VI that they were trained to recognize, discriminate and produce; *Timbre*—recognition of timbres from different instruments and voices; *Form*—children listened to classical music and to children's melodies.) Painting training emphasized the development of visuo-spatial performance on several components such as light and color, line, and perspective and material and texture. (Painting training was based on the following aspects: *Light-color*—children were trained to appreciate color as an expressive element in a visual composition. Exercises included mixing colors to create new ones, distinguishing different shades of the same hue, analyzing the impact of light and shading in color perception, and of color in form and space perception. Children were taught color categories [primary/secondary, hot/cold], color gradation, color contrast, color harmony and color symbolism and to differentiate color hues and brightness; *Line-perspective*—children practiced how to use visual elements like points, lines, plans and structures as expressive means; *Material-texture*—children worked with different types of materials [natural and artificial textures] and different kinds of drawing supports.) Children in the music group gave a public performance at the end of the school year and children in the painting group had a public exhibition of their artwork.

Phase 3 (3 weeks)
Children were again individually tested for neuropsychological assessments and pitch discrimination in 2 separate sessions that lasted for 2 h each, by using the same procedure and stimuli as in Phase 1.

ERP Recordings

Electroencephalogram (EEG) was continuously recorded using a portable Biosemi amplifier system (Amsterdam, BioSemi Active 2) from 32 active Ag–AgCl electrodes mounted on a child-sized elastic cap and located at standard positions (International 10/20 system sites). On-line recordings were referenced to the Common Mode electrode and were re-referenced off-line to the algebraic average of the left and right mastoids. In order to detect horizontal eye movements and blinks, the electro-occulogram was recorded from electrodes placed 1 cm to the left and right of the external canthi and from an electrode beneath the right eye. The bandpass was 0.01–30 Hz and data were digitized at a 500-Hz sampling rate by a laptop computer (Sony Vaio: Intel Pentium). EEG data were analyzed using the Brain Vision Analyser software (Version 01/04/2002; Brain Products, Gmbh). Recordings were segmented into 2200-ms epochs, starting 200 ms before final word or note onset. Trials containing ocular and movement artifacts, amplifier saturation or too much noise were excluded from the averaged ERP waveforms (mean = 20%).

Data Analysis

Except if mentioned otherwise, repeated measures analyses of variance (ANOVAs) were used to analyze data from the various neuropsychological tests and pitch discrimination tasks. They included Group (music vs. painting) as a between-subjects factor and Session (before vs. after training) as a within-subject factor. Depending upon the analysis, they also included specific within-subject factors as specified below.

ERPs to final words and notes were analyzed for correct responses only. Mean amplitudes were measured in selected latency windows determined both from visual inspection of the waveforms and from previous results (Magne et al. 2006). For both the music and speech tasks, ANOVAs were computed for midline and lateral electrodes separately using the same factors as described above (Group and Session) as well as Congruity (congruous vs. weak incongruity vs. strong incongruity) and Electrodes (Fz, Cz, Pz, and Oz) as within-subject factors for midline analyses. For lateral analyses, the scalp distribution of the effects was analyzed using Hemisphere (left vs. right), anterior–posterior dimension (3 regions of interest [ROIs]: fronto-central (F3, Fc1; Fc5, F4, Fc2, Fc6), central (C3, Cp1, Cp5; C4, Cp2, Cp6) and parietal (P3, PO3, P7; P4, PO4, P8) and Electrodes (3 for each ROI) as within-subject factors. Tukey tests were used for all post hoc comparisons. All *P*-values were adjusted with the Greenhouse-Geisser epsilon correction for nonsphericity. Reported are the uncorrected degrees of freedom and the probability level after correction.

Results

Neuropsychological Assessments

Performance in the reading task, as measured by the percentage of errors, was analyzed as described above and by including Word Type (simple vs. consistent vs. inconsistent words) as another within-subject factor. Results showed that the main effects of Session ($F_{1,30}$ = 44.06, $P < 0.001$) and Word Type ($F_{2,60}$ = 391.50, $P < 0.001$) were significant. Children made overall fewer errors after (13.4%, SD = 5.7) than before training (25.2%, SD = 10.0) and for Simple (5.1%, SD = 3.8) and Consistent words (6.7%, SD = 6.7) than for Inconsistent words (46.1%, SD = 12.3). Moreover, both the Group by Session and the Group by Session by Word type interactions were significant ($F_{1,30}$ = 4.06, $P < 0.05$ and $F_{2,60}$ = 5.72, $P < 0.005$, respectively). Results of Tukey tests showed that improvements after training were only significant in musically trained children and for inconsistent words (see Fig. 2).

Turning to the standardized tests, results showed first, that although the increase in full-scale IQ was larger in the music group (12 points, SD = 13.9) than in the painting group (7 points, SD = 7.3), results of the ANOVA showed a main effect of Session ($F_{1,30}$ = 22.80, $P < 0.001$) but no Group by Session interaction ($F_{1,30}$ = 1.41, $P > 0.20$).

Second, results of the ANOVA including verbal versus performance IQ showed main effects of Session ($F_{1,30}$ = 27.65, $P < 0.001$) and IQ type ($F_{1,30}$ = 5.92, $P < 0.02$) with a significant Session by IQ type interaction ($F_{1,30}$ = 16.79, $P < 0.001$): the improvement with training was significant for performance IQ (108.6 vs. 119.5, $P < 0.001$) but not for verbal IQ (105.4 vs. 106.1, $P > 0.25$). The Group by Session interaction was not significant ($F_{1,30}$ = 1.40, $P > 0.20$). When ANOVAs were computed on WISC indexes (Verbal Comprehension Index [VCI], and Perceptual Organization Index [POI]), results also showed significant improvements with training that were not different between groups, therefore reflecting general development, maturation and repetition effects.

Finally, although the improvement on the normalized digit span scores with training was larger in the music group (1.06, SD= 2.54) than in the painting group (0.06, SD= 2.43), results of the ANOVA showed no Group by Session interaction ($F_{1,30}$ = 1.29, $P > 0.20$).

Pitch Discrimination Tasks

Behavioral Data

Music. Results showed significant effects of Session ($F_{1,30}$ = 29.76, $P < 0.001$) and Congruity ($F_{2,60}$ = 26.21, $P < 0.001$). Overall, children made fewer errors after (21.5%) than before training (32.2%) and for Strong (12.9%) than for Congruous (23.5%) or Weak incongruities (43.9%; see Table 1). The Group by Session and/or Congruity interactions were not significant ($F_{1,30}$ = 1.38 and $F_{1,30}$ = 1.46, respectively, both $P > 0.20$). There was, however, a trend in this direction: results of Student *t*-tests showed that the improvement after training for weak incongruities was significant in the music group ($P < 0.006$) but

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not in the painting group ($P > 0.20$). By contrast, the improvement was similar in both groups for strong incongruities (music, $P < 0.006$ and painting, $P < 0.03$) and congruous endings ($P < 0.02$ in both groups).

Speech. Results showed significant effects of Session ($F_{1,30} = 26.56$, $P < 0.001$) and Congruity ($F_{2,60} = 99.02$, $P < 0.001$). Children made overall fewer errors after (10.8%) than before training (18.2%) and for Strong (3.5%) than Congruous (7.5%) or Weak incongruities (32.5%, see Table 1). Moreover, the Group by Session by Congruity interaction was significant ($F_{2,60} = 4.18$, $P < 0.02$). The Session by Congruity interaction was significant in the music group ($F_{2,30} = 7.34$, $P < 0.002$) but not in the painting group ($F < 1$). Results of Tukey tests showed that music training improved the discrimination of weak incongruities ($P < 0.001$) but not of congruous endings and strong incongruities ($P > 0.20$ in both conditions). Painting training had no significant effects (all $P > 0.70$).

Electrophysiological Data

To simplify results presentation and because the effects of training on pitch discrimination are of greatest interest, we only report results based upon significant Group by Session × Congruity interactions.

Music task. Results of the ANOVAs are summarized in Table 2 and mean amplitude values (in microvolt, μV) are presented in Table 3. The ERPs data are illustrated on Figures 3 (central electrodes) and 4 (lateral electrodes). In the 200- to 400-ms latency band, the Group by Session by Congruity interaction was significant ($P < 0.01$) at both midline and lateral electrodes. Moreover, the Session by Congruity interaction was significant in the music group ($P < 0.001$ at both midline and lateral electrodes). Musical training significantly enhanced the amplitude of the N300 to weak incongruities (mean amplitude before training = −2.01 μV and after training = −8.28 μV at midline electrodes and −1.85 vs. −6.92 μV at lateral electrodes, $P < 0.001$) but had no effects for congruous notes and strong incongruities ($P > 0.20$ in both conditions). The Congruity by Hemisphere by ROI was also significant in the music group ($P < 0.01$): the amplitude of the N300 was larger over right than left frontal regions (see Fig. 4). By contrast, the Session by Congruity interaction was not significant in the painting group at either midline or lateral electrodes. As can be seen from Table 3, painting training did not influence the mean amplitudes of the ERPs in any of the 3 conditions (see also Fig. 3).

Speech task. Results of the ANOVAs are summarized in Table 4 and mean amplitude values are presented in Table 5. The ERPs data are illustrated on Figures 5 (central electrodes) and 6 (lateral electrodes). Analyses were first conducted in the 200- to 400-ms, 400- to 700-ms, and 700- to 900-ms latency bands. Because the effects were similar in these 3 latency bands, we report the overall results in the 200- to 900-ms latency band. In this latency range, the Group by Session by Congruity was significant ($P < 0.001$) at both midline and lateral electrodes. Moreover, the Session by Congruity interaction was significant in the music group ($P < 0.001$ at both midline and lateral electrodes). Musical training enhanced the amplitude of a positive component that developed from 200 until 900 ms following the presentation of weak incongruities (mean amplitude before training = 2.31 μV and after training = 7.60 μV at midline electrodes and 0.80 vs. 5.52 μV at lateral electrodes, $P < 0.001$) and reduced the positivity to strong incongruities (12.18 vs. 6.79 μV at midline electrodes and 8.70 vs. 5.22 μV at lateral electrodes, $P < 0.01$). No training effects were found for congruous endings. In the painting group, the Session by Congruity interaction was not significant at either midline or lateral electrodes. As can be seen from Table 5, painting training did not influence the mean amplitudes of the ERPs in any of the 3 conditions (see also Fig. 5).

Discussion

Musical training improved reading skills and the discrimination of small pitch variations (weak incongruities) in speech. Moreover and as predicted, musical training influenced the

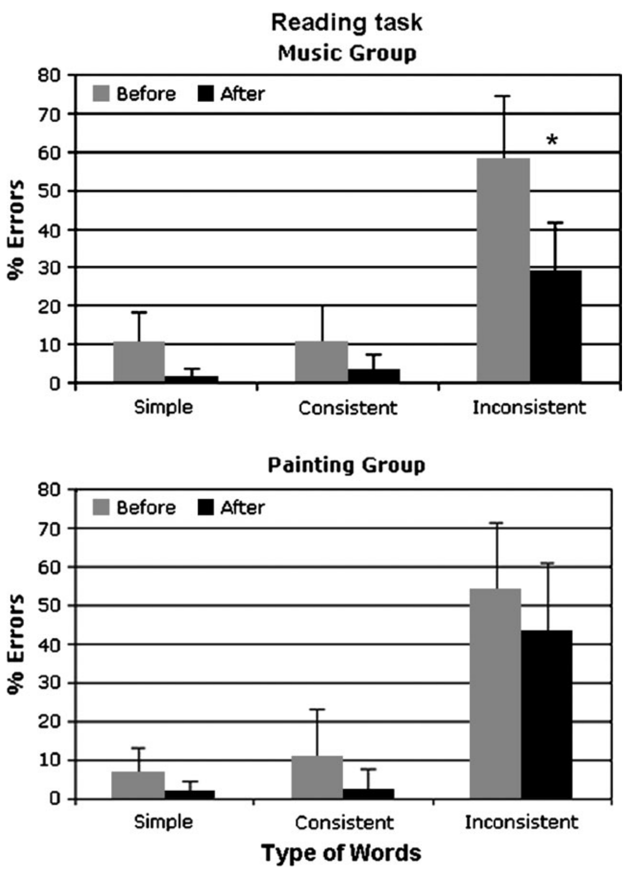

Figure 2. Percentage of errors in the Simple condition (24 words), Consistent condition (12 words), and Inconsistent condition (12 words) in the reading task. In the music and painting groups, the level of performance is compared before and after training: training effects are only significant in the music group for inconsistent words.

Table 1

Percentage of errors (SD in parentheses) to Weak (30 trials) and Strong (30 trials) incongruities and to Congruous endings (30 trials) in the Music and Language task for the Music and Painting training groups before and after training

Percent errors		Music group		Painting group	
		Before	After	Before	After
Music task	Weak	46 (25)	31 (24)	52 (21)	47 (26)
	Strong	15 (20)	3 (4)	22 (24)	12 (16)
	Congruous	31 (27)	19 (17)	27 (20)	17 (13)
Language task	Weak	38 (24)	19 (15)	41 (17)	32 (15)
	Strong	5 (10)	1 (1)	6 (7)	2 (4)
	Congruous	8 (11)	6 (5)	11 (8)	5 (5)

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amplitude of specific ERP components elicited in the music and speech tasks. Importantly, these effects were found although potential preexisting differences in perceptual and cognitive abilities were ruled-out because all children were nonmusicians and pseudorandomly assigned to the 2 training groups. Differences in cognitive stimulation and motivation between groups can also be ruled out because the children in the control group also participated in an equally stimulating

Table 2
Results of the ANOVAs for midline and lateral electrodes in successive latency bands from final note onset in the Music task

Latency bands (ms)	Electrode	Main	Music	Painting
100–200	Midline	G × S × C: ns	—	—
	Lateral	G × C × H: $F_{2,60}$ = 4.47**	C: $F_{2,30}$ = 16.93*** C × H × R: $F_{4,60}$ = 3.40**	C: $F_{2,30}$ = 4.80** C × H × R: ns
200–400	Midline	G × S × C: $F_{2,60}$ = 5.06**	C: $F_{2,30}$ = 11.61*** S × C: $F_{2,30}$ = 6.92***	C: $F_{2,30}$ = 5.37** S × C: ns
	Lateral	G × S × C: $F_{2,60}$ = 4.24**	C: $F_{2,30}$ = 11.50*** S × C: $F_{2,30}$ = 7.94*** C × H × R: $F_{4,60}$ = 3.99**	C: $F_{2,30}$ = 7.41*** S × C: ns C × H × R: ns
400–700	Midline	G × S × C: ns	—	—
	Lateral	G × S × C: ns	—	—

Note: G: Group; S: Session; C: Congruity; H: Hemisphere, R: ROI; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns: non significant.

Table 3
Mean amplitude (μV) values in the latency ranges of interest for the Music task

Latency bands (ms)	Electrode	Strong				Weak				Congruous			
		Music		Painting		Music		Painting		Music		Painting	
		S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
100–200	Midline	—		—		—		—		—		—	
	Lateral	−3.69		−1.89		−0.77		0.74		0.58		0.43	
200–400	Midline	−3.97		−2.96		−5.15		−2.58		0.40		0.86	
		−4.4	−3.5	−3.7	−2.2	−2.0	−8.3	−2.9	−2.3	0.2	0.6	1.9	−0.2
	Lateral	−4.52		−3.32		−4.38		−2.53		−0.61		0.39	
		−4.6	−4.5	−3.8	−2.8	−1.9	−6.9	−2.5	−2.6	−1.5	0.3	0.7	0.1

Note: S: Session.

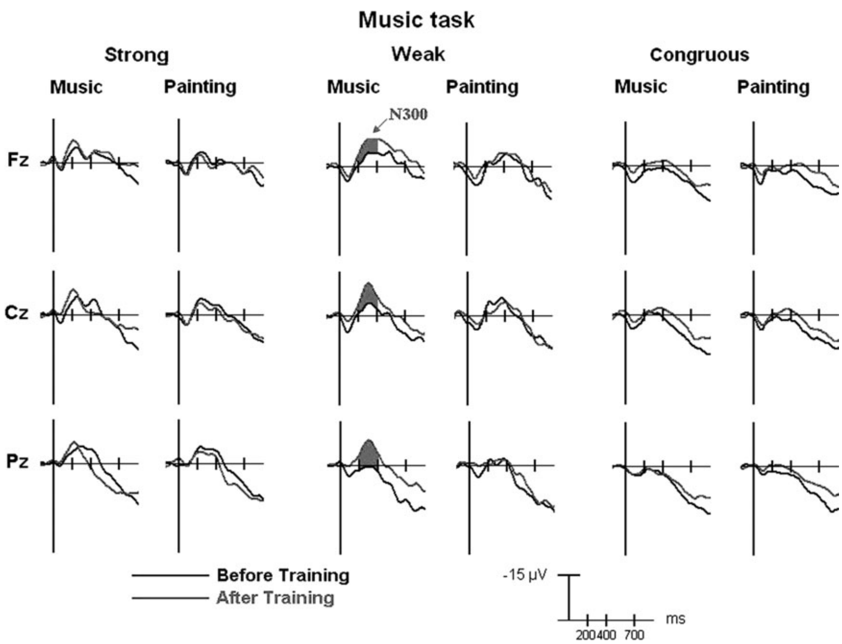

Figure 3. Music pitch discrimination task: averaged electrophysiological data across all children in the music (16 children) and painting (16 children) groups are presented for final strong and weak incongruities and for congruous notes. Recordings from 3 midline electrodes (Fz, Cz, and Pz), time-locked to final notes onset, are overlapped before (black line) and after training (gray line). The latency range within which statistical analyses revealed significant effects of training is highlighted in gray. An N300 component to weak incongruities developed after music training but not after painting training. In this and following figures, the amplitude (in μV) is plotted on the ordinate (negative up) and the time (in millisecond) is on the abscissa.

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extra-curricular activity, painting. Finally, comparing 2 groups of children allowed us to tease apart the effects that were specifically linked to musical training from those that might be due to normal development or maturation (all children were on average 6 months older after training) or due to practice with the tasks at hand (short gap—6 months between test and retest). Thus, improvements with training for performance IQ, for WISC indexes (VCI and POI), and for verbal memory (digit span) that were not different between groups (no Groups by Session interaction), were most likely driven by general development, maturation and repetition effects. By contrast, improvements in reading abilities as well as enhanced performance and ERP effects in the pitch discrimination tasks that differed between groups were most likely driven by musical training. Nurture rather than nature thus seems to account for the results reported here. Such an interpretation is also in line with results reported by Norton et al. (2005) showing no differences between children who were starting music lessons and those who were not.

Effect of Musical Training on Behavior

Results showed that training 8-year-old children with music improved reading skills specifically when phoneme-to-grapheme correspondence was complex. It is important to note that reading norms have recently been obtained from 272 Portuguese children for the development of a reading battery in Portuguese (ALEPE, Sucena and Castro, in press). The reading test that we used has been included in this battery and we checked that the level of performance on this test did correlate with other reading measures included in ALEPE. Good correlations (computed on the number of correct responses) were found between the present reading test and correct word reading per minute ($r(269) = 0.69$, $P < 0.001$; data from 269 children were available for this test) and with a Portuguese version of the French Lobrot L3 reading test ($r(181) = 0.55$, $P < 0.001$; data from 181 children were available for this test).

Moreover, the finding that music training improved reading skills is in line with the results of a large-scale study of 4- and 5-year-old children showing that music perception ability was

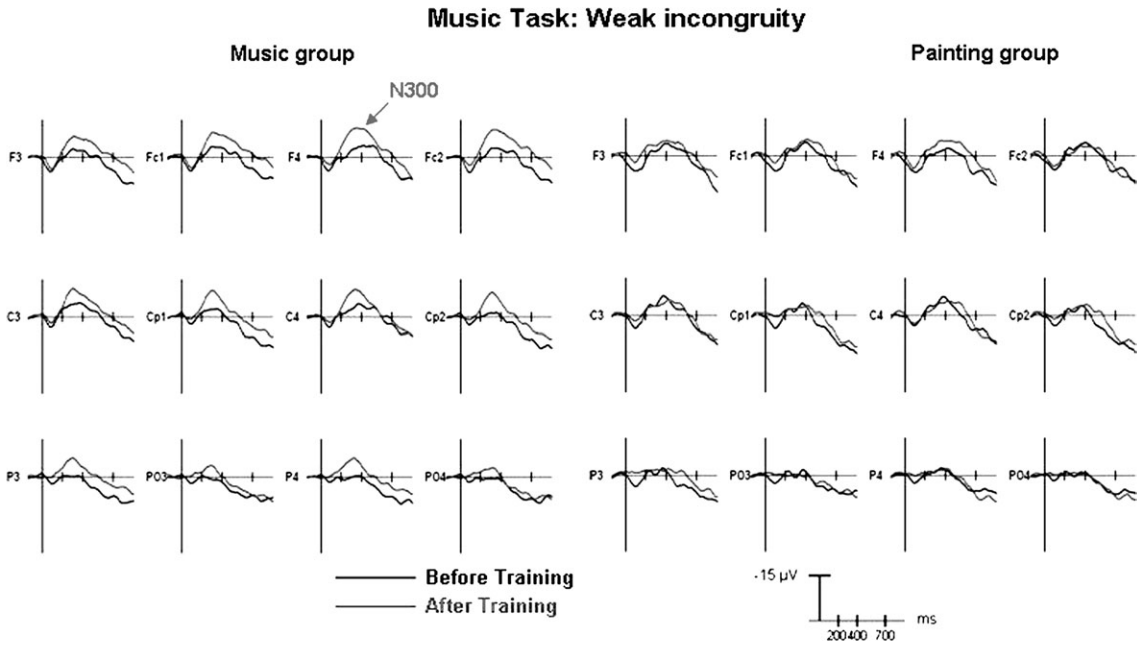

Figure 4. Music pitch discrimination task: averaged electrophysiological data in the weak incongruity condition are presented for children in the music and painting groups. Recordings from 12 representative lateral electrodes, time-locked to final weak incongruities onset, are overlapped before (black line) and after training (gray line). The N300 component developed across all electrodes in the music group but not in the painting group.

Table 4

Results of the ANOVAs for midline and lateral electrodes in successive latency bands from final word onset in the Speech task

Latency bands (ms)	Electrode	Main	Music	Painting
100–200	Midline	—	—	—
	Lateral	G × S × H: $F_{1,30} = 4.80$*	S × H: $F_{1,15} = 3.59^{\dagger}$ S × C: $F_{2,30} = 5.72$**	S × H: ns S × C: ns
200–900	Midline	G × S × C: $F_{2,60} = 5.86$***	C: $F_{2,30} = 54.55$*** C × E: $F_{4,60} = 11.28$*** S × C: $F_{2,30} = 22.75$***	C: $F_{2,30} = 35.50$*** C × E: $F_{4,60} = 5.36$*** S × C: ns
	Lateral	G × S × C: $F_{2,60} = 8.81$***	C: $F_{2,30} = 46.37$*** C × R: $F_{4,60} = 5.99$*** S × C: $F_{2,30} = 22.50$***	C: $F_{2,30} = 31.79$*** C × R: ns S × C: ns

Note: G: Group; S: Session; C: Congruity; H: Hemisphere; R: ROI; $^{\dagger}P = 0.07$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns: nonsignificant.

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Table 5

Mean amplitude (μV) values in the latency ranges of interest for the Speech task

Latency bands (ms)	Electrodes	Strong				Weak				Congruous			
		Music		Painting		Music		Painting		Music		Painting	
		S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
100–200	Midline	—		—		—		—		—		—	
	Lateral	0.6	−0.5	1.2	0.8	−2.4	1.1	−1.2	−1.1	−0.6	−1.1	0.1	−0.69
200–900	Midline	9.48		10.31		4.95		1.19		1.31		1.73	
		12	6.8	10	10	2.3	7.6	0.7	1.6	1.1	1.5	1.4	2.03
	Lateral	6.96		7.08		3.16		−0.17		0.12		0.08	
		8.7	5.2	6.5	7.6	0.8	5.5	−0.5	0.2	−0.5	0.5	−0.9	1.10

Note: S: Session.

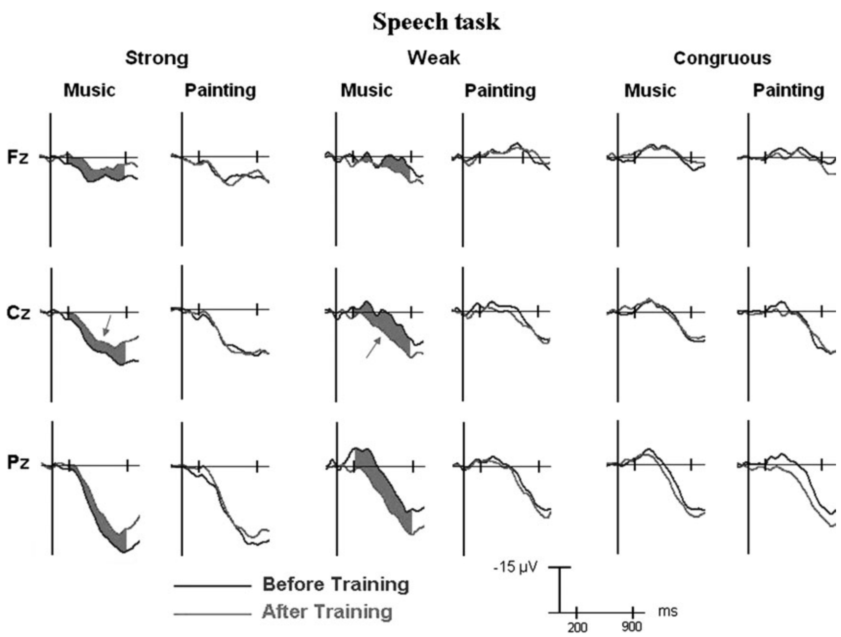

Figure 5. Speech pitch discrimination task: averaged electrophysiological data across all children in the music (16 children) and painting (16 children) groups are presented for final strong and weak incongruities and for congruous words. Recordings from 3 midline electrodes (Fz, Cz, and Pz), time-locked to final words onset, are overlapped before (black line) and after training (gray line). The latency range within which statistical analyses revealed significant effects of training is shown in gray. The amplitude of the positivity is increased after musical training for weak incongruities and is decreased for strong incongruities. No such effects are found after painting training.

predictive of reading skills (Anvari et al. 2002). Foxton et al. (2003) have also shown strong correlations in nonmusician adults between the ability to discriminate global pitch contour of sound sequences and phonological and reading skills.

Taken together, these results support the general hypothesis that musical training by improving basic auditory analysis, as well as sound segmentation and blending (Lamb and Gregory 1993), also improves the development of the phonological representations necessary for reading (Swan and Goswami 1997; Habib 2000; Anvari et al. 2002; Foxton et al. 2003; Overy 2003; Gaab et al. 2005; Tallal and Gaab 2006). Further support for this hypothesis comes from clinical studies showing that the severity of the reading problems of dyslexic adults is correlated with their difficulties to detect occasional frequency deviants among standard tones (Baldeweg et al. 1999). Moreover, using the same speech pitch discrimination task as was used here, dyslexic children also showed impaired pitch discrimination compared to control children, and abnormal neural correlates of pitch processing (Santos et al. 2007). Finally, Jäncke and collaborators (Kast et al. 2007) have recently shown that visual–auditory multimedia training for 3 months (by coupling reading and writing training with pitch and tone training) enhanced writing performance in children with developmental dyslexia and nondyslexic children. These new findings are in line with previous results from Standley and Hughes (1990) showing that music training improved pre-writing skills in 4- to 5-year children. The evidence is thus growing that shows a positive influence of music training on reading and writing abilities.

Musical training also improved pitch discrimination in speech, specifically when the incongruity was the most difficult to detect (small pitch variations; 28% errors across the 2 sessions). No such effects were found for the congruous and strong incongruities that were easier to detect (7 and 3% errors, respectively). Although a trend was observed in the same direction (as revealed by significant results of Student *t*-tests),

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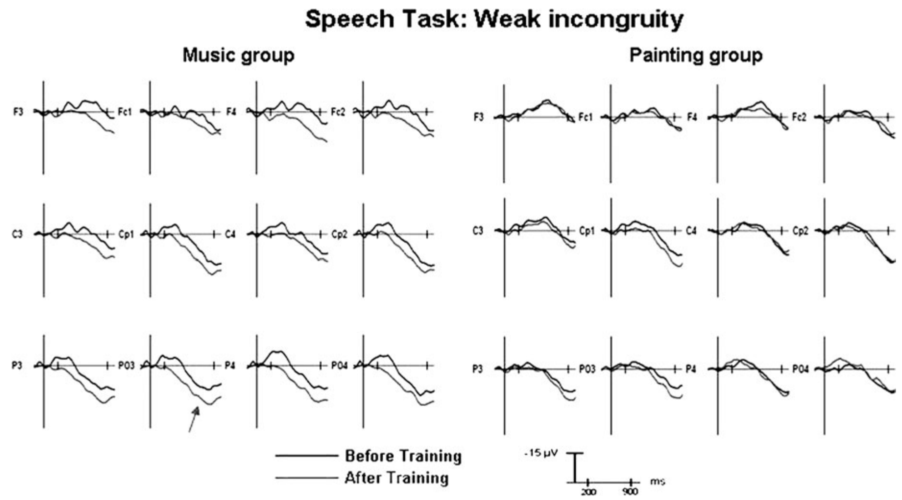

Figure 6. Speech pitch discrimination task: averaged electrophysiological data in the weak incongruity condition are presented for children in the music and painting groups. Recordings from 12 representative lateral electrodes, time-locked to final weak incongruities onset, are overlapped before (black line) and after training (gray line). The positivity increased across all electrodes in the music group but not in the painting group.

the influence of music training on the discrimination of small pitch variations in music was not significant in the general ANOVAs. This probably results from the fact that, whereas we tried to equate discrimination difficulty in both tasks subtle pitch variations were nevertheless more difficult to discriminate in music (38%) than in speech (28%). A longer training period therefore seems necessary to detect the weak incongruity in music.

The finding that musical training enhanced pitch discrimination in speech is in line with results of several experiments showing facilitatory effects of musical expertise on second language perception and learning. For instance, French adult musicians detect small pitch variations in a language that they do not understand (Portuguese) better than nonmusicians (Marques et al. 2007). Moreover, increased musical ability is correlated with increased phonological abilities in second language learning (Slevc and Miyake 2006) and with the learning of lexical tones that are used to differentiate word meaning in tone languages (Delogu et al. 2006; Wong and Perrachione 2007). In turn, the specific acoustic properties of languages have been shown to influence sound perception. In languages such as Finnish or Japanese (but not in German or French, for instance), differences in phonemes duration are linguistically relevant in that they signal differences in meaning. Tervaniemi et al. (2006) have shown that native Finish speakers detect duration differences in nonspeech sounds better than German speakers. Taken together, these findings argue for positive and reciprocal transfer effects between musical and linguistic abilities and for common pitch processing mechanisms in music and speech (but see below). They consequently have interesting consequences for second language learning and for teaching methods.

Finally, based upon Schellenberg' (2004) results showing-small, but significant, increases in full-scale IQ of 6-year-old children after one year of musical training (compared to control children that received drama lessons or no lessons) we expected to find similar results here. Although there was a trend in this direction, with larger increases in full-scale IQ after music than after painting training, this effect did not reach significance. Several factors, such as the duration of the training period (shorter here than in Schellenberg's study), the type of training, the number of children and the age difference between children in these 2 studies may account for these differences.

Effects of Musical Training on Neural Processes

May be most importantly, by training children with music we were able to generate electrophysiological effects in both music and speech that were similar to those previously found in 8-year-old children with 4 year of musical training (Magne et al. 2006). Considering music results first, the correct discrimination of small pitch variations (weak incongruities) at the end of musical phrases was associated with an increase in the amplitude of the N300 component after music training but not after painting training. Fujioka et al. (2006) recently reported an enhanced negative magnetic evoked response (N250m) to violin tones in musically trained children compared to untrained children. It is interesting that such similar components (N300 and N250m) were found while using different brain imaging methods (MEG and EEG) and different materials (single tones vs. musical phrases). These 2 components may, however, reflect functionally different processes because the N250m is larger over the left hemisphere while, in line with adult data on pitch processing, the N300 is larger over the right hemisphere. For instance, Bosnyak et al. (2004) trained nonmusicians to different sound frequencies for half an hour per day for 2 weeks. The amplitude of the auditory evoked potentials N1c and P2 was enhanced after such a short training and the N1c enhancement was larger over the right than left hemisphere. Although it remains difficult to establish a direct correspondence between ERP components in children and adults, the most important point may be that, in both adults and children, short-term musical training seems to produce effects that are similar to those observed with long-term musical training (Menning et al. 2000; Bangert et al. 2001, 2006; Haueisen and Knosche 2001; Pascual-Leone 2001; Tremblay et al. 2001; Atienza et al. 2002; Bosnyak et al. 2004; Fujioka et al. 2006; Magne et al. 2006; Shahin et al. 2003, 2004).

Increases in the amplitude of auditory ERP components with musical practice are often considered as reflecting an increased

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efficiency of the neural networks involved in pitch/frequency processing (because more neurons are active or because their activity is more synchronized; e.g., Shahin et al. 2003). The N300 enhancement to weak incongruities reported here may reflect such processes. Alternatively, the N300 enhancement may also reflect the difficulty of stimulus categorization and the extra-attention required to discriminate small changes in pitch (Fujioka et al. 2006). In line with this interpretation, learning to play a musical instrument might train attention and concentration more than learning to paint. Note, however, that these 2 interpretations are not incompatible or mutually exclusive: attention may act by increasing the number and the activity of neurons that are tuned to the stimuli (Bosnyak et al. 2004). To further examine this issue, attentive and preattentive processes will be tested in future experiments.

Turning to the speech results, the correct discrimination of small pitch variations (weak incongruities) of the sentence final words was associated with an increase in the amplitude of a long-lasting positivity after music training but not after painting training. This effect that developed as early as 200-ms postsentence-final word onset and lasted until 900 ms most likely encompasses different perceptual (pitch analysis) and cognitive processes (categorization and decision). The finding that musical training influences the brain electrical activity associated to the processing of linguistic pitch patterns provides evidence for transfer effects from music to speech processing. This conclusion is supported by recent results of Wong et al. (2007) showing that the coding of the acoustic attributes of linguistic pitch patterns is more faithfully represented in the brainstem auditory responses of musicians than of nonmusicians. Consequently, both short and long-term musical training seems to influence the processing of basic acoustic cues, such as pitch, that are relevant to both music and speech.

In line with our hypothesis, such transfer effects argue for common pitch processing in music and speech. However, if common mechanisms are involved in the processing of musical and linguistic pitch patterns, why are the effects different when small pitch variations are embedded in musical stimuli (N300) and in speech stimuli (long-lasting positivity starting at 200 ms)? A possible answer relies on the lower level of difficulty of the speech compared to the musical discrimination task. If, as argued above, the N300 enhancement reflects the difficulty of stimulus categorization and the extra-attention required to discriminate small changes in pitch, it would not develop when the pitch discrimination is easy. Alternatively, the N300 may start to develop in the speech task, but its development may be cut-short by an early-onset (200 ms) overlapping positivity associated with stimulus discrimination and categorization. Such an effect has been recently described by Marques et al. (2007). The issue of the similarity of pitch processing in music and speech therefore needs to be further considered in future experiments.

Finally, it should be noted that, in contrast to weak incongruities, the positivity to strong incongruities in speech was reduced after training in the music group. This outcome was predicted on the basis of previous results obtained with 8-year-old nonmusician French children musically trained for 8 weeks (Moreno and Besson 2006) and is interpreted as reflecting the automation of pitch processing with musical training and the smaller size/greater efficiency of the neural networks necessary to perform the task at hand (e.g., Batty and Taylor 2002). Such an interpretation is supported by results of fMRI experiments showing decreased activation in different brain regions with increased musical practice (Jancke et al. 2000; Koeneke et al. 2004).

In conclusion, the present data add to the growing evidence, building on both animal (Anderson et al. 1994, 2002; Markham and Greenough 2004) and human studies, in adults and children, which shows that relatively short periods of training have profound consequences on the anatomical and functional organization of the brain (e.g., Draganski et al. 2004). By addressing specific hypotheses based on our previous results (Magne et al. 2006), and by conducting longitudinal studies with pseudorandom assignment of nonmusician children to equally interesting and motivating experimental and control groups, we have been able to demonstrate the specific role of musical training in normally developing children. This influence has been shown to generalize from music to speech perception and reading skills; these transfers highlight the commonality of pitch processing in music and speech as well as the influence of attention processes (Besson and Schön 2001; Maess et al. 2001; Gaser and Schlaug 2003; Patel 2003; Koelsch et al. 2002, 2003, 2005). Importantly, however, this does not imply that there are no naturally occurring variations in pitch perception abilities, or that these variations have no genetic basis. Drayna et al. (2001), for instance, have demonstrated that pitch perception is more similar in monozygotic than dizygotic twins, thereby highlighting heritable differences in auditory functions.

By increasing our understanding of how musical training influences behavior and brain activity, the present results should benefit research-based education programs and should help develop new methods to improve the abilities of children with abnormal development (Posner and Rothbart 2005; Schlaug et al. 2005; Goswami 2006; Tallal and Gaab 2006; Santos et al. 2007). They also open new research perspectives. Further comparing pitch processing in music and speech using stimuli and tasks varying in levels of complexity and different brain imaging methods, determining whether the effects reported here are long-lasting, testing for the influence of musical training on other aspects of speech perception, such as rhythm or timbre, and determining whether the influence of music generalizes to other domains such as second language learning or mathematics, are exciting research topics for the years to come.

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