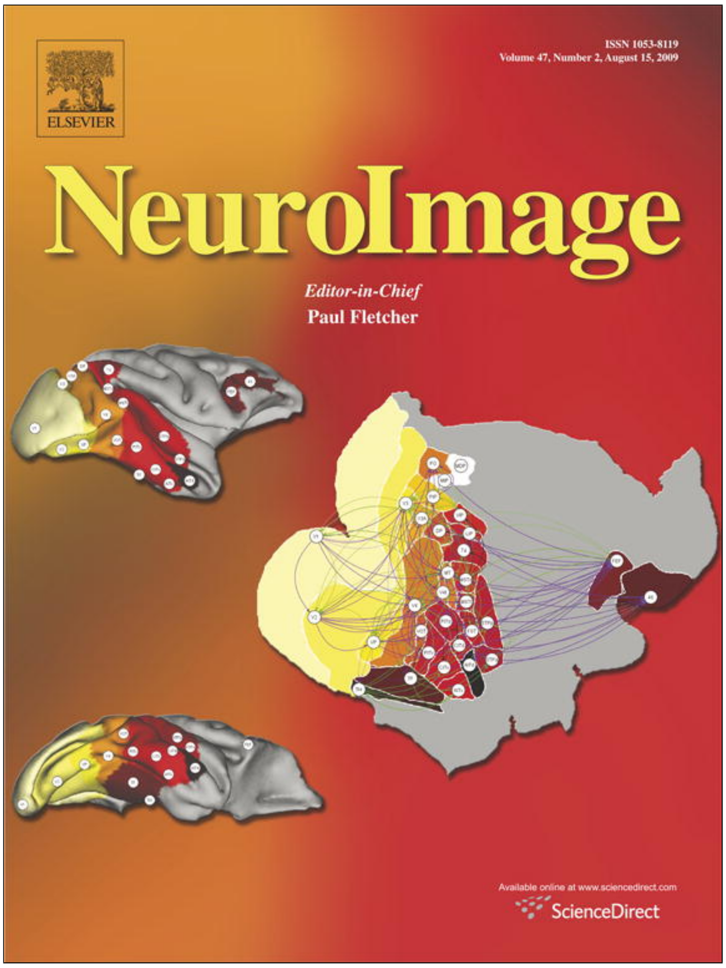
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Musical training modulates the development of syntax processing in children

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ABSTRACT

The question of how musical training can influence perceptual and cognitive abilities of children has been the subject of numerous past studies. However, evidence showing which neural mechanisms underlie changes in cognitive skills in another domain following musical training has remained sparse. Syntax processing in language and music has been shown to rely on overlapping neural resources, and this study compared the neural correlates of language- and music-syntactic processing between children with and without long-term musical training. Musically trained children had larger amplitudes of the ERAN (early right anterior negativity), elicited by music-syntactic irregularities. Furthermore, the ELAN (early left anterior negativity), a neurophysiological marker of syntax processing in language, was more strongly developed in these children, and they furthermore had an enlarged amplitude of a later negativity, assumed to reflect more sustained syntax processing. Thus, our data suggest that the neurophysiological mechanisms underlying syntax processing in music and language are developed earlier, and more strongly, in children with musical training.

Introduction

Both music and language consist of perceptually discrete elements that are combined into structured sequences according to highly complex regularities. The arrangement of these elements into sequences is governed by a set of principles that is commonly denoted as syntax. The human brain internalises these regularities by mere exposure, and the acquired implicit knowledge influences perception and performance (see Saffran, 2001, 2003; Saffran et al., 1996; Tillmann et al., 2000, 2003b).

A violation of music-syntactic regularities, induced by irregular chord functions occurring within a chord sequences (or by irregular tones occurring in melodic sequences; cf. Miranda and Ullman, 2007), usually elicits two ERP components: An early right anterior negativity (ERAN) and a later negativity (N5) (Koelsch, 2005, 2009 [for a review]; Koelsch et al., 2000, 2002c; Leino et al., 2007; Loui et al., 2005; Miranda and Ullman, 2007). These components can be observed in 30 month old children (Jentschke, 2007; accessible at: http://edoc.mpg.de/get.epl?fid=51414&did=394818&ver=0), indicating that already these children process chords according to their harmonic regularity. The amplitude of the ERAN can be modulated by musical training (Koelsch et al., 2002b), underlining that more specific representations of musical regularities lead to heightened musical expectancies. Usually, the ERAN is followed by a late negativity, the N5 (maximal around 500 ms), which is taken to reflect processes of musical integration (Koelsch, 2005; Koelsch et al., 2000; Steinbeis and Koelsch, 2008).

Violations of the phrase structure of a sentence usually elicit an early left anterior negativity (ELAN) and a late positivity (P600) (Friederici and Kotz, 2003 [for a review]; Friederici et al., 1993; Hahne and Friederici, 1999). The ELAN is assumed to reflect automatic initial structure building, which involves the identification of the incoming word's syntactic category upon which a local syntactic structure is built. The age at which the ELAN can be observed depends upon the type of linguistic material: For sentences with passive mode construction (as used in the present study), an ELAN appears at 12 to 13 years of age. In younger children, a later, sustained anterior negativity in response to a syntactic violations (henceforth referred to as LSN) may be found, assumed to reflect more sustained linguistic syntax processing (Hahne et al., 2004). For sentences with active mode construction, an ELAN can already be found in 32 month old children (Oberecker et al., 2005). The P600 is thought to reflect secondary parsing processes under strategic control, and to be involved in structural integration (Friederici et al., 1998; Hahne and Friederici, 1999; see also Friederici & Kotz, 2003, and Kaan et al., 2000, for a discussion).

The domain-specificity or domain-generality of syntactic processing has attracted considerable attention during the last years (Caplan and Waters, 1999; Koelsch and Siebel, 2005; Lewis et al., 2006; Patel, 2008; Peretz and Coltheart, 2003). There is some evidence in favour of the idea that music and language draw on a common pool of limited processing resources for integrating incoming elements into syntactic structures (Patel, 2003): The main neural generators of ERAN and ELAN, which reflect contextually independent, automatic structure-

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building processes, are located in overlapping brain areas. These are especially the lateral parts of the inferior frontal gyrus and the superior temporal gyrus (for language: Friederici et al., 2000; Heim et al., 2003; for music: Koelsch et al., 2005a, 2002a; Maess et al., 2001; Tillmann et al., 2003a). Furthermore, these ERP components are similar in polarity and latency (both are negativities with a maximum amplitude approximately 200 ms after stimulus onset).

In addition to the overlap in the neural correlates, a functional interaction between the processing musical and linguistic syntax has been observed in a number of studies. ERP studies revealed that brain responses to linguistic-syntactic violations are reduced when a morpho-syntactically irregular word is presented synchronously with a music-syntactically irregular chord (Koelsch et al., 2005b; Steinbeis and Koelsch, 2008). Physically deviant tones (that did not represent a music-syntactic violation) did not induce an amplitude reduction in the brain responses to linguistic-syntactic violations, and music-syntactic violations did not influence semantic processing (as indexed by the N400 amplitude; Koelsch, 2005). Recently, a behavioural experiment (Slevc et al., 2009) showed that reading times for syntactically, but not for semantically, irregular words were increased when presented together with a music-syntactic violation (another experiment by Fedorenko et al., 2009, revealed comparable results). That is, speed and accuracy of linguistic-syntactic processing were modulated by music-syntactic complexity.

The anatomical and functional overlap of resources involved in the syntactic processing of language and music motivated us to evaluate whether musical training would influence the processing of linguistic syntax. Because of the multimodal nature and the intensity of musical training, musicians are ideally suited to investigate the various aspects of complex skill acquisition, learning and brain plasticity (see Münte et al., 2002; Schlaug, 2001 for overviews). Musical training can lead to anatomical and functional differences, influencing several processing stages during music perception or production (see, e.g., Koelsch et al., 2002b, 1999; Pantev, 1999; Pantev et al., 1998, 2001; Rüsseler et al., 2001; Schneider et al., 2002). It may also cause transfer effects to other cognitive domains, such as language, e.g. an improved processing of linguistic pitch patterns (Wong et al., 2007), and of prosody (Magne et al., 2006; Neuhaus et al., 2006; Schön et al., 2004), as well as improved reading skills (Anvari et al., 2002; Moreno et al., 2009), and perhaps improved verbal working memory (Chan et al., 1998 [in adults]; Ho et al., 2003 [in children]; Kilgour et al., 2000). However, so far very few studies investigated the neural mechanisms responsible for the transfer of abilities that were acquired by musical training, to other cognitive domains, and (to our knowledge) no study has explored whether such transfer effects would include such complex processes as those required for syntax processing in language.

To determine the influence of musical training on the neurophysiological correlates of syntax processing, we conducted a within-subject comparison of the ERP responses to violations of musical or linguistic syntax in 10-to-11-year old children with and without musical training. This age group was chosen for two reasons: Firstly, because we assumed that the musically trained children would have had a sufficient amount of musical training for transfer effects to arise. Secondly, previous evidence (Hahne et al., 2004) showed that the processing of phrase structure violations is still under development during this age: At least for sentences with passive mode construction, children in this age group typically do not show an adult-like ERP response to this kind of linguistic-syntactic violation. Thus, we expected that the ERAN and the ELAN (as well as the LSN) would differ between the two groups. However, we did not expect a group difference for the N5, because previous studies did not report such group differences for the N5 either (cf. Koelsch et al., 2002b; Miranda and Ullman, 2007).

Materials and methods

Participants

Two groups of 10-to-11-year old children, either with or without musical training, were compared. All children were native speakers of German, and right-handed (according to the Edinburgh Handedness Inventory; Oldfield, 1971). None of them suffered from any known

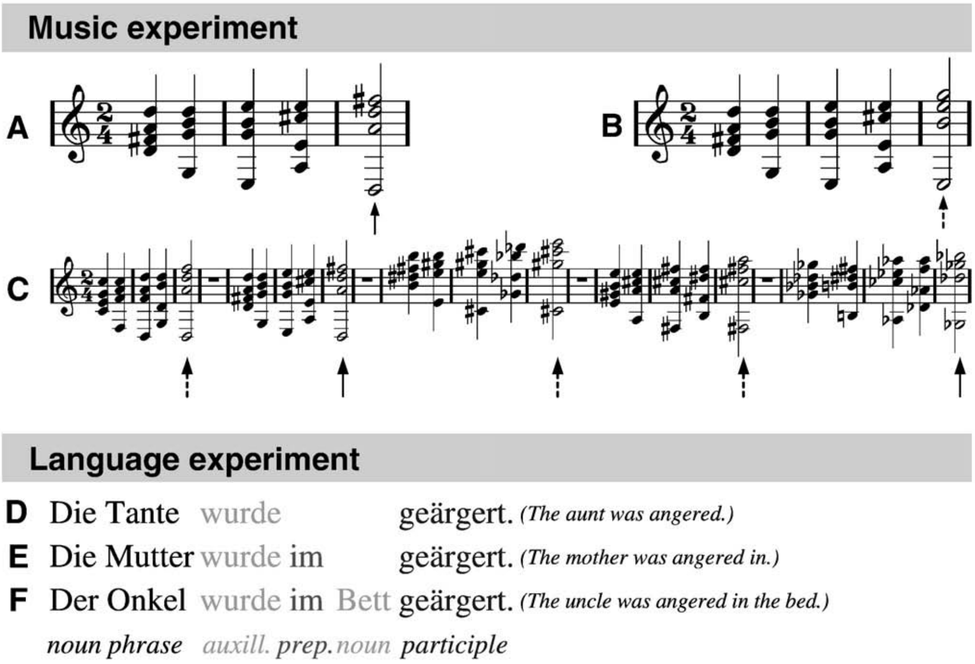

Fig. 1. A–C: Examples for chord sequences used in the music experiment. These sequences were ending either on a regular tonic (A), or on an irregular supertonic (B). They were played in direct succession (C). **D–F**: Examples of the sentence types used in the language experiment. The noun phrase, the auxiliary and the participle are contained in all sentences. The syntactically correct sentence contained just these four words (D). The syntactic violation was introduced by a preposition that was not followed by a noun (E). In the filler sentences the complete prepositional phrase (preposition and noun) was presented (F).

hearing or neurological deficits, attention deficit disorders, reading or learning disabilities (e.g., dyslexia). Children were excluded, if [1] their EEG measurements could not be evaluated (e.g., due to many artefacts); [2] they learned a foreign language before the age of 6 years; [3] they had problems or delays in language acquisition; [4] they had learning problems (e.g., attention deficits or an verbal IQ of less than 80 points); or [5] they started to learn an instrument, but gave up playing it. Their parents gave written informed consent.

Children with musical training (MT; $N=24$) were recruited from the St. Thomas Boys Choir and from the public music school in Leipzig. 21 of these children were evaluated (12 boys, 9 girls; 10;1 to 11;7 years old, $M=10;8$ years). They played an instrument for 2;9 to 6;7 years ($M=4;9$ months). Children without musical training (NM; $N=31$) did not learn an instrument, did not sing in a choir, and received no extracurricular music lessons. They were recruited from public schools in Leipzig. 20 children were evaluated (10;3 to 11;10 years old, $M=11;1$ years; 9 boys, 11 girls).

Three classes of variables were employed to control for the educational and the socio-economic background of the children: First, the verbal part of the WISC-III was used in order to match the two groups with respect to the educational background of the children. It was also used to exclude participants scoring below the low average range (i.e. 80 IQ points). Second, the occupation of both parents was classified in terms of the "International Standard Classification of Occupation 1988" (International Labour Organization, 1990) which then was transformed into "International Socio-Economic Index of Occupational Status" values (Ganzeboom and Treiman, 1996) to provide a status measure for this occupation. Third, we obtained the duration of education (in years) of both parents. Importantly, there was no significant group difference in these variables (for a detailed overview, please see the Results).

Stimuli and paradigm

Each participant was tested twice: In one session they underwent music- and in the other session a language experiment (with the order of sessions being counter-balanced across participants). Each of these sessions comprised of two blocks (each lasting about 20 min) in which the children listened to chord sequences or sentences (described in detail below). In the first (attentive) block, they listened to the stimuli while looking at a fixation cross; in the second (non-attentive) block, they listened while watching a silent movie. Between the two blocks in each session, the subtests of the verbal part of a standardized intelligence test were administered.

In each block of the ***music session***, children listened to chord sequences, identical to those of previous studies exploring music-syntactic processing (Jentschke et al., 2008 [with children]; Koelsch et al., 2007 [with adults]). There were two types of sequences (Figs. 1A, and B), each consisting of five chords. The first four chord functions (tonic, subdominant, supertonic, and dominant) did not differ between sequences. The final chord function of sequence type A was a harmonically regular tonic, and that of type B a music-syntactically irregular supertonic. Presentation time of the chords was identical to previous studies (e.g., Koelsch et al., 2000): 600 ms for chords 1 to 4, 1200 ms for the final chord, which was followed by a 1200 ms silence period. Notably, music-syntactic irregularity did not co-occur with physical deviance (cf. Koelsch et al., 2007). Sequences were transposed to the 12 major keys, resulting in 24 different sequences. All sequences were played with a piano sound with the same decay of loudness for all chords (generated using Steinberg Cubase SX and The Grand; Steinberg Media Technologies, Hamburg, Germany). Both sequence types were randomly intermixed (with a probability of 0.5 for each sequence type), and presented in direct succession via loudspeakers (Fig. 1C). Moreover, each sequence was presented pseudo-randomly in a tonal key different from the key of the preceding sequence.

Across each block of the session, each sequence type was presented eight times, resulting in an amount of 192 sequences. Additional 18 sequences contained one chord played by a deviant instrument. The task of the children was to respond to these timbre deviants with a key press (this task was employed to control for the children's attention).

The ***language session*** employed a paradigm used in a number of previous studies to investigate the processing of linguistic syntax (Friederici et al., 1993 [in adults]; Hahne et al., 2004 [in children]). Correct, incorrect and (correct) filler sentences (see Figs. 1D to F) were presented in a pseudo-randomised order. These sentences consisted of at least four words which had the same grammatical function, i.e., an article, a noun, an auxiliary and a past participle (see bottom line in Fig. 1). The syntactically correct sentences (Fig. 1D) consisted only of these four words. A syntactic violation was introduced by sentences in which a preposition appeared after the auxiliary, directly followed by a past participle (Fig. 1E), thereby leading to a phrase structure violation. Because the preposition indicates the beginning of a prepositional phrase – necessarily consisting of a preposition and a noun phrase – this sequence of words creates a clear word category violation. Filler sentences (Fig. 1F) that consisted of the whole prepositional phrase (i.e., a preposition followed by a noun phrase) were introduced to disguise that sentences of interest induced a syntactic violation and to ensure that participants were not able to anticipate the violation when encountering the preposition. These sentences were therefore not evaluated. The critical word on which an error became overt was the participle, which was identical for all three types of sentences.

Across each block of the session, the children listened to 240 sentences (96 correct, 96 incorrect and 48 correct filler sentences), presented in a pseudo-randomised order. In 32 sentences one word was replaced by the same word spoken by a male voice instead of the standard female voice (16 of them were presented within the filler sentences, another 8 of them each in the correct and the incorrect sentences; all these sentences were not evaluated). As in the music experiment, the task for the children was to respond to these timbre deviants with a key press (to control for their attention).

EEG recording and processing

During these two experimental sessions, EEG data were recorded with Ag-AgCl electrodes from 27 locations: 22 scalp locations – FP1, FP2, F7, F3, FZ, F4, F8, FC3, FC4, T7, C3, CZ, C4, T8, CP5, CP6, P7, P3, PZ, P4, P8, O1, O2 according to the Extended International 10–20 System (American Electroencephalographic Society, 1994) – and 5 additional electrodes placed on the nose tip, outer *canthi* of both eyes, left and right mastoids. Data were sampled at 250 Hz, with a reference at the left mastoid and without online filtering using a PORTI-32/MREFA amplifier (TMS International B.V., Enschede, NL). Impedances were kept below 3 kΩ for the scalp electrodes, and below 10 kΩ for the additional electrodes.

The EEG data were processed offline using EEGLab 4.515 (Delorme and Makeig, 2004): They were re-referenced to the mean of left and right mastoid, and filtered with a 0.25 Hz high-pass filter to remove drifts (finite impulse response [FIR], 1311 pts) and a 49–51 Hz band-stop filter to eliminate line noise (FIR, 437 pts). Artefacts caused by eye blinks, eye movements, and muscular activity were removed using an independent component analysis (ICA). Data were rejected if amplitudes exceeded ± 100 μV, if linear trends exceeded 120 μV in a 400 ms gliding time window, if the trial was lying outside a ± 6 SD range (for a single channel) or ± 3 SD range (for all channels) of the mean probability distribution, or the mean distribution of kurtosis values, and if spectra did deviate from baseline by ± 30 dB in the 0 to 2 Hz frequency window (to reject eye movements) and $+15/-30$ dB in the 8 to 12 Hz frequency window (to reject alpha activity). Non-rejected epochs were averaged: In the music session ($M=19.3\%$

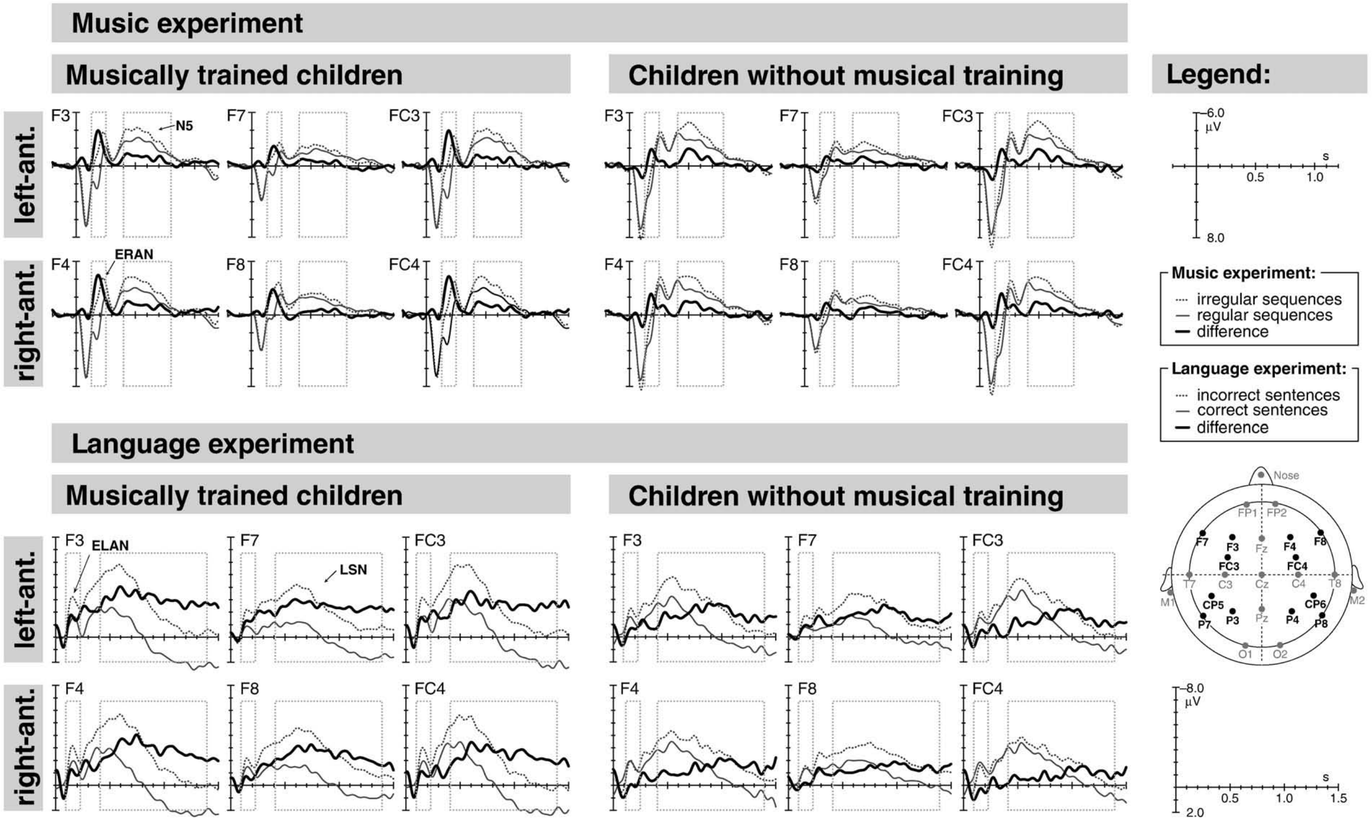

Fig. 2. ERPs from the music (upper panel) and the language experiment (bottom panel): The group means are given in separate panels — from the group of musically trained children (MT) at the left side and from the group of children without musical training (NM) at the right side. In the upper rows of each panel the electrodes from the left-anterior ROI are shown, the bottom rows contain the electrodes of the right-anterior ROI (only the anterior ROIs are shown, as these are the main site of effect). Thin black dotted lines represent the ERP response to the irregular chords (in the music experiment) or to the syntactically incorrect sentences (in the language experiment), thin black solid lines the ERP response to the regular chords or to the syntactically correct sentences. The thick black solid lines indicate the difference of these conditions. The ERPs are averaged across the two blocks of each session (attentive and non-attentive), because there were no interactions of *syntactic regularity* and *attentiveness*, except for the LSN. Electrodes that are contained in the ROIs used for statistical evaluation are written in black in the figure of their head position.

rejected trials) from 0 to 1200 ms after stimulus onset (length of the final chord) with a baseline from -200 to 0 ms; in the language session ($M = 21.6\%$ rejected trials) from 0 to 1500 ms with a baseline from 0 to 100 ms. Time windows for evaluation were chosen based on visual observation, and according to previous studies using the same paradigms in children (Hahne et al., 2004; Koelsch et al., 2003).

Statistical evaluation

Behaviourally, the children were asked to respond with a button press to the deviant instrumental timbre (in the music experiment) or a change in the voice of the speaker (in the language experiment). We evaluated both the proportion of correct responses and the reaction times using ANOVAs with the within-subject factors *session* (music *vs.* language) and *attentiveness* (attentive *vs.* non-attentive block), and the between-subjects factor group (MT *vs.* NM).

For the statistical evaluation of the ERP data, four regions of interest (ROIs) were computed (see schematic head in Fig. 2): left-anterior (F7, F3, FC3), right-anterior (F4, F8, FC4), left-posterior (CP5, P7, P3), and right-posterior (CP6, P4, P8). Two time windows were evaluated in the music session: [1] 140 to 340 ms (ERAN), [2] 400 to 800 ms (N5); and in the language session: [1] 120 to 320 ms (ELAN), and [2] 400 to 1400 ms (later sustained negativity in response to a syntactic violation; LSN). We furthermore compared the brain response between 300 to 500 ms (N400) to the first content word (the noun) in the sentences to ensure that the expected transfer effects were specifically targeting the processing of syntactic regularities. None of the variables used in the analyses did deviate from a standard normal distribution ($0.19 \le p \le 1.00$; Median $= 0.85$).

Mixed-model ANOVAs for repeated measurements were used to evaluate these ERP responses (separately for each ERP component). These ANOVAs were computed with the within-subject factors *anterior–posterior distribution*, *hemisphere* (left *vs.* right), and *attentiveness* (looking at a fixation cross *vs.* watching a silent movie), as well as the between-subjects factor group (MT *vs.* NM). The experimentally manipulated (within-subject) factor *syntactic regularity* compared the brain response to regular *vs.* irregular chords in the music experiment, and to the sentence final word (the past participle) in the syntactically correct *vs.* the incorrect sentences. The results of all ANOVAs are summarized in Table 2 with *F*- and *p*-values (which will not be reported again in the text). Within these ANOVAs, user-defined contrasts were employed to specify separately for each ROI the scalp distribution of effects (considering both groups together), and to specify whether the amplitude of this particular ERP component was significantly larger in the group of the MT compared to the NM children. Whenever any interaction of *syntactic regularity* × *group* was significant, two further ANOVAs (with the same within-subject factors as the ANOVAs above) were computed, separately for each group of children, to examine the respective component in either group. For the evaluation of the ELAN (which previously had been demonstrated to develop until 12 to 13 years, cf. Hahne et al., 2004), a further ANOVA with the same factors as above, but *age* (in months) as covariate was employed (similar analyses, with age as a covariate, were performed for the other ERP components, but neither of these revealed any significant interactions involving *age* and *syntactic regularity*).

To evaluate whether the expected transfer would specifically affect the processing of linguistic syntax, or whether it would also influence the semantic processing, we compared the N400 to the first target word (the noun) in all sentences (i.e., we pooled syntactically correct and incorrect sentences in the attentive and the non-attentive blocks). This ERP response was compared between the two groups in an ANOVA with the within-subject factors *anterior–posterior distribution*, and *hemisphere* (left *vs.* right), and the between-subjects factor *group* (MT *vs.* NM).

We aimed to match the groups with respect to gender, age, socio-economic background, and verbal IQ. However, we were not completely successful with matching the gender (12 boys and 9 girls in the MT group *vs.* 9 boys and 11 girls in the NM group). Hence, we calculated further ANOVAs, introducing *gender* as additional between-subjects factor. None of these analyses revealed any significant interaction involving *syntactic regularity* and *gender*. The duration of education and the socio-economic status of the parents, as well as the verbal IQ of the children, were compared between groups with *t*-tests for independent samples. Even though none of the variables differed significantly between groups, the duration of mother's education was approaching significance (see below). For this reason, we explored possible influences of these variables in correlations analyses, involving the amplitude of the ERP components of interest on the one hand, and the variables of the socio-economic background (father's and mother's duration of education and their occupational status) on the other hand. Parents also provided further information on the health status of the children, their educational background, their language acquisition, their musical background (e.g. learned instruments), and other familial variables (e.g. number of siblings), none of which was significantly correlated with any of the ERP variables.

Results

Behavioural data

Participants detected almost every of the trials with deviant instruments ($M = 97.8\%$) or the deviant voice timbre ($M = 97.2\%$), with a higher amount of correct responses in the attentive block ($M = 99.2\%$) compared to the non-attentive block ($M = 95.9\%$), reflected in a main effect of *attentiveness* ($F_{(1,39)} = 6.69$; $p = 0.014$). The MT group had a slightly better performance ($M = 98.4\%$) than the NM group ($M = 96.6\%$).

The reaction times were shorter for the music ($M = 541$ ms) than the language session ($M = 603$ ms), and for the attentive ($M = 540$ ms) compared to the non-attentive blocks ($M = 603$ ms). The reaction times difference between the blocks was larger in the language session ($M = 94$ ms) than in the music session ($M = 31$ ms). This was reflected in a main effects of *session* (music *vs.* language; $F_{(1,39)} = 25.39$; $p < 0.001$), *attentiveness* ($F_{(1,39)} = 35.81$; $p < 0.001$) and

Table 1
Mean amplitude and standard error of mean (in parentheses) for the evaluated ERP components (ERAN, N5, ELAN, and LSN).

Group	Region	Hemisph.	ERAN	N5	ELAN	LSN
MT and NM	Anterior	Left	−1.60 µV (0.27 µV)	−0.93 µV (0.20 µV)	−0.94 µV (0.24 µV)	−2.19 µV (0.24 µV)
		Right	−1.93 µV (0.29 µV)	−0.79 µV (0.22 µV)	−0.26 µV (0.20 µV)	−1.83 µV (0.26 µV)
	Posterior	Left	−0.56 µV (0.18 µV)	−0.16 µV (0.21 µV)	0.01 µV (0.16 µV)	−0.16 µV (0.21 µV)
		Right	−0.75 µV (0.18 µV)	−0.18 µV (0.19 µV)	0.01 µV (0.16 µV)	0.39 µV (0.24 µV)
MT	Anterior	Left	−2.31 µV (0.39 µV)	−0.88 µV (0.26 µV)	−1.32 µV (0.34 µV)	−2.79 µV (0.33 µV)
		Right	−2.75 µV (0.45 µV)	−0.79 µV (0.23 µV)	−0.69 µV (0.33 µV)	−2.57 µV (0.35 µV)
NM	Anterior	Left	−0.88 µV (0.36 µV)	−0.98 µV (0.32 µV)	−0.55 µV (0.35 µV)	−1.60 µV (0.35 µV)
		Right	−1.11 µV (0.36 µV)	−0.79 µV (0.38 µV)	0.17 µV (0.22 µV)	−1.10 µV (0.39 µV)

For the evaluation of the whole group anterior and posterior ROIs are reported, for the comparison of the MT and the NM children only the anterior ROIs.

an interaction of both ($F_{(1,39)} = 6.40$; $p = 0.016$). As for the correct responses, the performance in the MT ($M = 543$ ms) was better than in the NM group ($M = 600$ ms). Despite the better performance, both ANOVAs did not reveal main effects or interactions with *group* ($p \geq 0.217$).

ERP results

Music experiment

ERAN. In both groups, an ERAN was elicited in response to the irregular compared to regular chords (see Table 1 and Fig. 2). It had an anterior, bilateral (slightly right-lateralized) distribution, and peaked around 240 ms. In the musically trained (MT) children, the amplitude size (at the anterior ROIs) was more than twice as large as in the children with no musical training (NM; see Table 1). The predominance of this effect at anterior, especially at right-anterior scalp sites, as well as the larger ERAN amplitude in the MT children (compared to the NM children) can best be seen in the isopotential maps of Fig. 3.

An ANOVA (see Table 2) revealed a main effect of *syntactic regularity*, an interaction of *syntactic regularity* × *group*, and an interaction of *syntactic regularity* × *anterior–posterior distribution*. Separate analyses for each sub-group revealed a similar pattern of results. Even though the effect was most pronounced at frontal electrodes, planned comparisons with user-defined contrasts revealed a broadly distributed ERAN, which was significant at all four ROIs when both groups were considered (left-anterior: $F_{(1,39)} = 35.55$, $p < 0.001$; right-anterior: $F_{(1,39)} = 44.70$, $p < 0.001$; left-posterior: $F_{(1,39)} = 9.72$, $p = 0.003$; right-posterior: $F_{(1,39)} = 17.81$, $p < 0.001$). The ERAN amplitude was significantly larger in the MT compared to the NM group in the left-anterior ($F_{(1,39)} = 7.06$, $p = 0.011$), right-anterior ($F_{(1,39)} = 8.03$, $p = 0.007$), and right-posterior ROIs ($F_{(1,39)} = 6.04$, $p = 0.019$).

N5. The N5 (see Table 1 and Fig. 2) peaked around 500 ms, and was most pronounced at the anterior ROIs. Its amplitude was virtually identical for both groups, although slightly more focused in the MT children, and slightly broader in the NM children (see Fig. 3).

An ANOVA (see Table 2) revealed a main effect of *syntactic regularity*, and an interaction of *syntactic regularity* × *anterior–posterior distribution*. User-defined contrasts revealed a significant N5 at the anterior ROIs (left: $F_{(1,39)} = 21.15$, $p < 0.001$; right: $F_{(1,39)} = 13.00$, $p = 0.001$) when both groups were considered together. The difference between the groups was not significant at any ROI.

Language experiment

ELAN. An ELAN with a latency of around 160 ms was elicited mainly in the MT children (see Table 1 and Fig. 2), where the amplitude size was about five times larger than in the NM group. The ELAN was most pronounced at the electrodes in the left-anterior ROI, considerably smaller at the right-anterior ROI, and virtually absent at the posterior ROIs. The isopotential maps of Fig. 3 show the amplitude maximum at

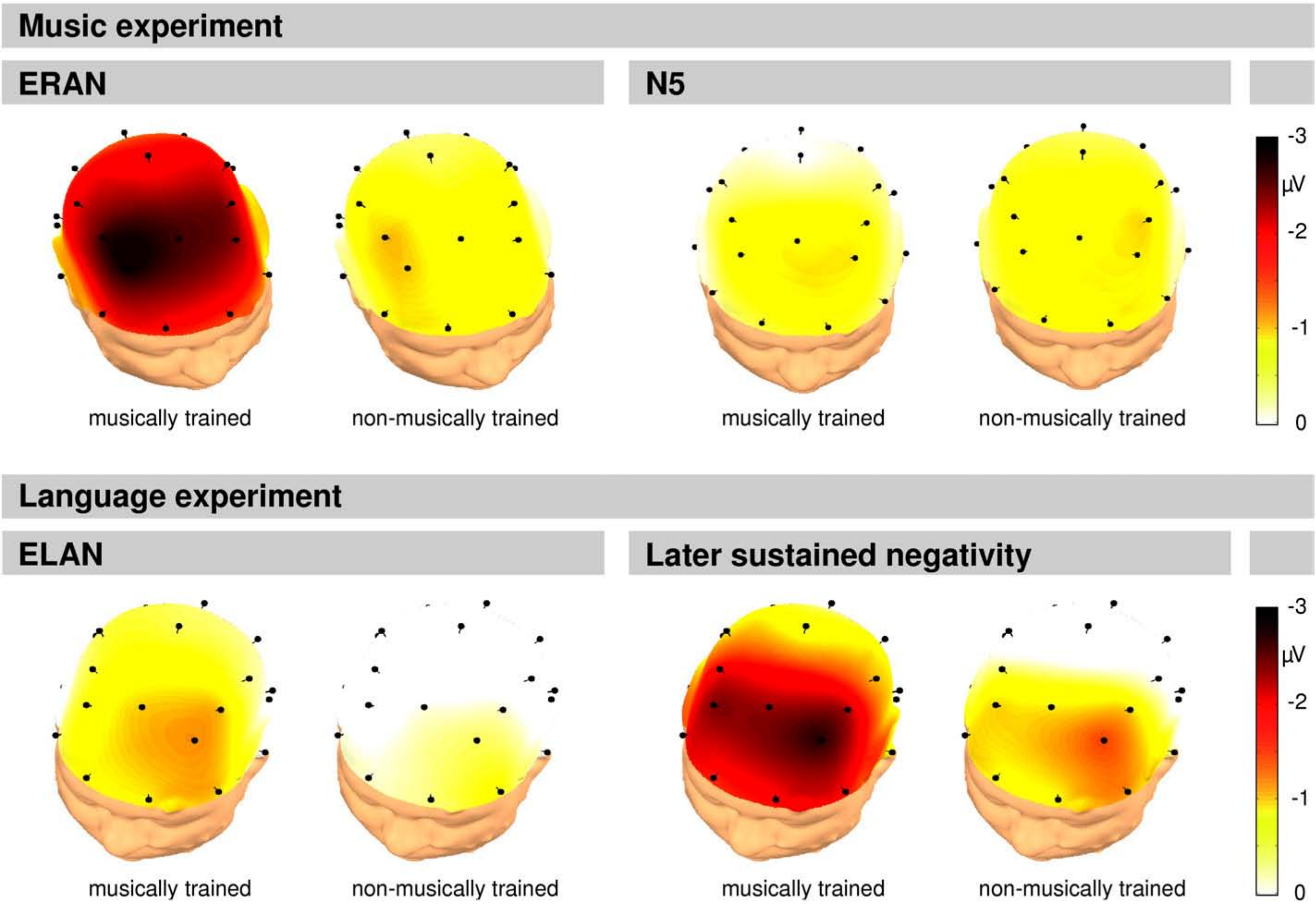

Fig. 3. Scalp topographies (isopotential maps) of the investigated ERP components (ERAN, N5, ELAN, and LSN). The topographies are a spherical spline interpolation of the amplitude difference between either irregular and regular chords (ERAN and N5) or syntactically incorrect and correct sentences (ELAN and LSN). The time windows were identical to those used for the statistical analyzes. In the upper panel the ERPs from the music experiment, in the bottom panel these from the language experiment are shown. For each ERP component the head plots from the children with musical training (MT) are on the left side, the head plots from the children without musical training (NM) are on the right side.

Table 2
Overview of the results of the ANOVAs used to statistically evaluate the four ERP components (ERAN, N5, ELAN, and LSN).

	ERAN		N5		ELAN		LSN	
	$F_{(1,39)}$	p	$F_{(1,39)}$	p	$F_{(1,39)}$	p	$F_{(1,39)}$	p
regularity	42.69	<0.001	8.76	0.005	3.60	0.065	34.58	<0.001
regularity × group	8.98	0.005	0.15	0.700	4.01	0.052	5.82	0.021
regularity × group × hem. × attent.	1.68	0.203	0.14	0.714	0.26	0.615	4.20	0.047
regularity × region	22.15	<0.001	19.20	<0.001	9.12	0.004	75.79	<0.001
regularity × region × hemisphere	0.65	0.424	0.68	0.416	16.21	<0.001	7.66	0.009
regularity × region × attention	0.76	0.390	1.10	0.300	0.13	0.719	6.07	0.018
regularity × hemisphere	3.94	0.054	0.26	0.616	4.44	0.042	0.18	0.675
group	4.64	0.038	0.29	0.596	4.74	0.036	0.18	0.677
group × attention	0.37	0.548	7.37	0.010	12.11	0.001	4.63	0.038
region	0.16	0.688	97.30	<0.001	59.19	<0.001	64.46	<0.001
region × hemisphere	1.33	0.255	9.71	0.003	0.00	0.951	0.61	0.441
region × attention	10.40	0.003	4.65	0.037	5.78	0.021	12.55	0.001
hemisphere	6.00	0.019	19.98	<0.001	0.02	0.885	0.42	0.521
hemisphere × attention	2.39	0.130	3.02	0.090	1.28	0.265	12.90	0.001

These had the factors syntactic regularity (regularity), anterior–posterior distribution (region), hemisphere, attention (fixation cross *vs.* silent movie), and group (musically trained *vs.* non-musically trained children). Effects are reported only when they were significant in at least one ANOVA. Main effect and interactions with syntactic regularity are listed in the upper part of the table.

left frontal scalp sites, as well as the presence of the ELAN in the MT children, but its virtual absence in the NM children.

An ANOVA (see Table 2) revealed interactions of *syntactic regularity × anterior–posterior distribution*, of *syntactic regularity × anterior–posterior distribution × hemisphere*, and of *syntactic regularity × hemisphere*. This reflects that the ELAN was most pronounced at the left anterior electrodes. Planned comparisons, used to determine the site of effect, showed a significant difference at the left-anterior ROI ($F_{(1,39)} = 14.93$, $p < 0.001$) when both groups were considered. Furthermore, the ELAN amplitude was found to be significantly larger in the MT group (compared to the NM group) at the right-anterior ROI ($F_{(1,39)} = 4.58$, $p = 0.039$). Because the ELAN amplitude (as measured at the anterior ROIs) was much larger in the MT group than in the NM group, we expected to find an interaction of *syntactic regularity × group*, which, however, was minimally above the significance threshold ($F_{(1,39)} = 4.01$; $p = 0.052$).

It seems reasonable to expect that the ELAN amplitude would vary with age, given that the ELAN was shown to develop until around 12 to 13 years of age (for sentences with passive mode construction; cf. Hahne et al., 2004). Thus, an ANOVA with *age* (in months) as additional covariate was computed. In this ANOVA, the interaction of *syntactic regularity × group* was clearly significant ($F_{(1,38)} = 5.91$, $p = 0.020$). Further, an interaction of *syntactic regularity × anterior–posterior distribution × hemisphere* ($F_{(1,38)} = 4.21$, $p = 0.047$) indicated that the ELAN was most pronounced at the left-anterior ROI, and an interaction of *syntactic regularity × anterior–posterior distribution × hemisphere × age* ($F_{(1,38)} = 4.96$, $p = 0.032$), reflecting the influence of age on the ELAN amplitude.

To further explore the ELAN in the two groups, two ANOVAs (one for each group) were calculated. In the MT group, the ANOVA with *age* as a covariate revealed an interaction of *syntactic regularity × anterior–posterior distribution × hemisphere* ($F_{(1,19)} = 9.50$, $p = 0.006$) and an interaction of *syntactic regularity × anterior–posterior distribution × hemisphere × age* ($F_{(1,19)} = 11.29$, $p = 0.003$). This reflects that an ELAN was observed in the MT group (most pronounced at left-anterior scalp sites), and that the ELAN amplitude was modulated by the age of the participants. In the NM group, neither a main effect nor interactions with *syntactic regularity* were found, indicating that an ELAN was not yet established in this group.

Later sustained negativity. During the time period in which the neural mechanisms underlying the generation of the ELAN develop, a later sustained negativity (LSN) can be observed (sometimes in addition to the ELAN) in response to the linguistic syntax violation (cf. Hahne et al., 2004). It appeared as a negative, sustained amplitude difference with a later onset than the ELAN. The children of the present study also showed such an LSN (see Table 1 and Fig. 2), being most pronounced at the left-anterior ROI. There was almost no ERP difference between regular and irregular words in the LSN time-window at the posterior ROIs. In contrast to the strongly left-lateralized ELAN, this ERP component was rather bilaterally distributed at the anterior ROIs (see Fig. 3). Importantly, the amplitude of the LSN was considerably larger in the MT group than in the NM group.

An ANOVA (see Table 2 for detailed results) revealed a main effect of *syntactic regularity*, as well as interactions of *syntactic regularity × group*, of *syntactic regularity × group × hemisphere × attention*, of *syntactic regularity × anterior–posterior distribution*, of *syntactic regularity × anterior–posterior distribution × hemisphere*, and of *syntactic regularity × anterior–posterior distribution × attention* (a similar pattern of results was obtained in the separate ANOVAs for each group). User-defined contrasts revealed that this ERP component was significant only at the anterior ROIs (when both groups were considered; left-anterior: $F_{(1,39)} = 84.36$, $p < 0.001$; right-anterior: $F_{(1,39)} = 48.59$, $p < 0.001$), as well as significantly larger in the MT group compared to the NM group at the same ROIs (left-anterior: $F_{(1,39)} = 6.24$, $p = 0.017$; right-anterior: $F_{(1,39)} = 7.74$, $p = 0.008$).

The LSN was the only ERP component where the availability of attentional resources caused significant differences in the amplitude size, reflected in an interaction of *syntactic regularity × group × hemisphere × attention*: Whereas an amplitude reduction was observed for the NM group at both anterior ROIs (*left-anterior*: −1.94 μV *vs.* −1.25 μV; *right-anterior*: −1.48 μV *vs.* −0.73 μV), and the left-anterior ROI in the MT group (−3.38 μV *vs.* −2.19 μV), no such reduction was observed at the right-anterior ROI (−2.55 μV *vs.* −2.58 μV). That is, the cognitive processes reflected by this ERP component at the right-anterior ROI seem not to be influenced by the availability of attentional resources in MT children.

N400. To ensure that the influence of musical training specifically targets linguistic syntax processing, we explored semantic processing in both groups by comparing the brain response (N400) to the first target word in the sentence. We found neither a significant main effect nor any interactions with *group* ($p > 0.150$). That is, the neurophysiological correlates of syntactic, but not of semantic, language processing significantly differed between groups.

Parents' duration of education and socioeconomic status (ISEI), non-verbal IQ, and gender. We aimed to match the two groups of children with regard to their parents' education and socioeconomic status (ISEI — Ganzeboom and Treiman, 1996). This was done to ensure that observed differences in the processing of linguistic and musical syntax would not be influenced by such factors, but by a

Table 3
Mean values and standard error of mean (in parentheses) for the values denoting the socio-economic status (ISEI values) and the education of the parents (duration of education in years) as well as the verbal IQ of the children (IQ points).

	Parents' education		Socioeconomic status		Verbal IQ
	Mother	Father	Mother	Father	
Children with musical training	17.05	16.32	61.80	62.29	122.19
	(0.71)	(0.56)	(4.00)	(3.13)	(2.29)
Children without musical training	15.18	15.75	58.56	57.94	119.95
	(0.74)	(0.82)	(4.03)	(4.41)	(2.22)

different amount of musical training. The group means of these measures are summarized in Table 3. Small differences in the duration of parents' education were observed, that were slightly larger for the mothers than for the fathers, but this difference did not reach statistical significance (mother: $t_{(34)} = 1.83$, $p = 0.075$; father: $t_{(33)} = 0.58$, $p = 0.565$). The group difference in the parents' socioeconomic status were also small (slightly larger for the fathers), and statistically not significant (mother: $t_{(34)} = 0.56$, $p = 0.578$; father: $t_{(35)} = 0.83$, $p = 0.414$). Furthermore, there was no group difference in the verbal IQ values ($t_{(39)} = 0.70$, $p = 0.487$).

Even though both groups did not differ significantly with respect to a number of variables reflecting the socio-economic background, the difference in the maternal duration of education was relatively large (and approaching statistical significance). However, not any significant correlation of maternal education with the amplitude size of the explored ERP components was observed ($r \leq 0.167$; $p \geq 0.331$; tested at the frontal ROIs). In contrast, the status of the maternal occupation (ISEI) seems to be a more critical variable: For this variable correlations with the amplitude of the two language ERP components were observed (ELAN, left-frontal ROI: $r = 0.485$, $p = 0.004$; LSN, left-frontal ROI: $r = 0.394$; $p = 0.023$; LSN, right-frontal ROI: $r = 0.558$; $p = 0.001$). For this variable, the two groups were well matched ($p = 0.578$). Therefore, it is unlikely that these socioeconomic variables account for the observed group difference in linguistic-syntactic processing.

Similarly, we were not able to perfectly match the gender in both groups (9 girls and 12 boys in the MT group *vs.* 11 girls and 9 boys in the NM group). However, when testing whether gender has a significant influence on the ERP components, none of the ANOVAs revealed any significant interactions involving *syntactic regularity* and *gender*.

Discussion

Our study explored whether musical training modulates the neurophysiological mechanisms underlying syntax processing in music and language in 10-to-11-year old children. In the music experiment, we observed that the ***ERAN*** amplitude was almost twice as large in MT children compared to NM children. This corroborates previous studies with both children (Koelsch et al., 2005a) and adults (Koelsch et al., 2005a, 2002b), and presumably reflects that MT children had a more comprehensive knowledge of music-syntactic regularities, and were, therefore, more sensitive to the violation of such regularities. However, an ERAN was observed in both groups. In line with previous studies, it had a slightly increased latency compared to adults (Jentschke et al., 2008; Koelsch et al., 2003) and a rather bilateral scalp distribution (Jentschke et al., 2008 [in children]; Koelsch, 2009 [for a discussion]; Loui et al., 2005 [in adults]).

No group differences were observed for the ***N5***, similar to previous studies comparing adult musicians and non-musicians (Koelsch et al., 2002b; Miranda and Ullman, 2007) where a group difference for the ERAN, but not for the N5 was observed. The N5 is taken to reflect processes of musical integration, and interacts with language-semantic processing (Steinbeis and Koelsch, 2008), giving rise to the notion that the N5 is related to the processing of musical meaning (Koelsch, 2005; Steinbeis and Koelsch, 2008). The present results corroborate this view, showing that musical training influenced syntactic (ERAN and ELAN), but not semantic processing (N5 and N400).

Importantly, our results show that musical training also modulates neurophysiological mechanisms underlying the processing of linguistic syntax: An ***ELAN*** was found in the MT group, but not in the NM group. In line with a previous study (Hahne et al., 2004), the ELAN (as observed in the MT children) had a peak latency of around 160 ms and its scalp distribution was maximal at left-anterior scalp electrodes. The data of the MT children show that the processes underlying the generation of the ELAN are still developing, as indicated by the importance of age as a covariate when evaluating the ELAN. This is consistent with previous evidence showing that the ELAN usually develops until the age of 13 (Hahne et al., 2004). The presence of the ELAN only in MT children indicates that processes of fast and fairly automatic syntactic structure building (cf. Hahne and Friederici, 1999) are developed earlier in these children.

The observed transfer effect (i.e., the effect of musical training on the ELAN) can be accounted for by the overlap of the neural resources, especially in the *inferior frontal gyrus* (IFG), that are involved in syntax processing of music and language. Previous studies showed that musical training leads to a volume increase in this brain region (Sluming et al., 2002, 2007; participants of both studies were adults), as well as to increased brain activity (in both adults and children) when processing music-syntactic irregularities (Koelsch et al., 2005a). However, it is also possible that the observed modulation of the neurophysiological mechanisms was, at least partly, elicited by more general processing components that are involved in, but not specific for, syntactic processing: Essential for both music- and language-syntactic processing is sequential processing in which words and chords (or tones) are related to each other according to their function and their position in a syntactic structure. The IFG plays a crucial role for sequential processing (see Bornkessel et al., 2005; Gelfand and Bookheimer, 2003; Janata and Grafton, 2003; Mesulam, 1998), for the prediction of future events (Fuster, 2001; Rao et al., 2001; Schubotz et al., 2000), and for the control and programming of actions (cf. e.g. Mars et al., 2007; Rizzolatti and Craighero, 2004 [for a review]; Rubia et al., 2006). Therefore, the training of movement sequences (as required for playing an instrument and singing) might have contributed to the transfer effect observed in this study. Future studies could determine whether the processing of structured sequences in other domains is also modulated by musical training (which would specify the domain-generality of the mechanisms responsible for transfer effects such as those observed in the present study).

The right IFG is not only involved in the processing of musical syntax (e.g. Koelsch et al., 2005a), but also in the processing of prosody (see Friederici and Alter, 2004 [for a model]; Meyer et al., 2002; Wartenburger et al., 2007). This might be a reason why musical training can facilitate the processing of prosody (cf. Magne et al., 2006; Moreno and Besson, 2006). Furthermore, the processing of prosody and linguistic syntax has been shown to interact (Eckstein and Friederici, 2006), and such an interaction might also have contributed to the transfer effects observed in this study.

No P600 (which usually follows the ELAN) was observed in the present study, due to the experimental design in which the syntactic irregularity was not task-relevant (consistent with previous studies with adults, Hahne and Friederici, 1999). However, in addition to the ELAN, a late syntactic negativity (***LSN***) was evoked in both groups but with an enlarged amplitude in the MT children. Compared to the ELAN, it had a later onset (around 400 ms), a sustained amplitude, and a relatively bilateral scalp distribution (cf. Hahne et al., 2004). It likely reflects later linguistic-syntactic processing which is more under attentive control (as reflected by the interactions involving *syntactic* *regularity* and *attentiveness* which were observed only for this ERP component). The LSN was significant in both groups, but its amplitude was almost two times larger in the MT compared to the NM children. This presumably reflects more comprehensive syntactic knowledge in MT children. Future studies could explore this in more detail.

Previous studies indicated that musical training can improve general cognitive abilities (cf. Schellenberg, 2004, 2006). In contrast, our data demonstrate that musical training modulates neurophysiological mechanisms underlying the processing of musical and linguistic syntax, or possibly, more generally, the structural processing of complex regularity-based sequences. A key argument for rather specific effects of musical training on syntactic processing is that group differences were observed for neural correlates of syntactic (ERAN, ELAN and LSN), but not for correlates of semantic processing (N400 and N5).

It is unlikely that pre-existing differences between the MT and the NM children, e.g. in terms of basic auditory processing skills, account for the observed difference in syntax processing (although an experimental design with a baseline measurement would have been desirable in order to prove this). A previous study indicates that there are no neural, cognitive, motor, or musical differences between children who start to learn an instrument and those who do not (Norton et al., 2005). Furthermore, in our study, variables that were shown to correlate with behavioural and brain measures of language skills (cf. Noble et al., 2007; Raizada et al., 2008), were either matched, or did not correlate with the amplitude of ERP components. Thus, it is most likely the musical training which is responsible for modifications in the neurophysiological mechanisms underlying musical and linguistic syntax processing.

Although we observed that musical training modulates the development of the neural mechanisms underlying language-syntactic processing, we have no data about possible behavioural consequences of this modulation. Based on previous evidence one might hypothesize that reaction times to linguistic-syntactic violations might be decreased following musical training: Given that a diminished amplitude of an ERP component reflecting linguistic-syntactic processing when encountering a music-syntactic violation at the same time (Koelsch et al., 2005b) had a behavioural counterpart in an increased reaction time to a linguistic-syntactic violation (Slevc et al., 2009), one might assume that the heightened amplitude of the ELAN in the MT children could have a behavioural correlate in a diminished reaction time. This is well in accordance with the assumption that the ELAN reflects fast and highly automatic aspects of syntax processing. Therefore, the observed modulation of the neurophysiological mechanisms underlying linguistic syntax processing after musical training might translate into faster syntax processing in language. However, this assumption remains to be explored in future studies.

Conclusion

The present study demonstrates that the neurophysiological correlates of musical as well as of linguistic–syntactic processing are more strongly (and in the case of the ELAN earlier) developed in children with musical training. This strengthens the view of a close relation between music- and language-syntactic processing. Our findings indicate that musical training does not only influence music perception and production, but also very complex processing mechanisms in another cognitive domain, namely language.

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