ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Volume 999

THE NEUROSCIENCES AND MUSIC

Edited by Giuliano Avanzini, Carmine Faienza, Diego Minciacchi, Luisa Lopez, and Maria Majno

The New York Academy of Sciences
New York, New York
2003

Toward the Neural Basis of Processing Structure in Music

Comparative Results of Different Neurophysiological Investigation Methods

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Abstract: In major-minor tonal music, chord functions are arranged according to certain regularities. The dominant-tonic progression, known as an authentic cadence, is often used as a marker of the end of a harmonic progression and has been considered a basic syntactic structure of major-minor tonal music by several music theorists and music psychologists. We review data from studies in which brain responses to an authentic cadence were compared to those elicited by music-syntactically inappropriate endings. In event-related electric brain potentials (recorded with EEG), the inappropriate endings elicit early right anterior negativity (ERAN), which is maximal around 200 ms after the presentation of an inappropriate chord. The ERAN is reminiscent of early anterior negativities elicited by syntactic incongruities during the perception of language. Magnetoencephalographic (MEG) data suggest that the ERAN is generated in the inferior frontolateral cortex, an area known to be crucially involved in the processing of (linguistic) syntax. Interestingly, the ERAN can be recorded in nonmusicians and in children, indicating that the ability to acquire (implicit) knowledge about musical regularities and to process musical information according to this knowledge is a general ability of the human brain. This ability is probably of great importance for the acquisition of language in infants and children.

Keywords: music; EEG; event-related potential (ERP); structure; syntax; ERAN; music-syntactic mismatch negativity (MMN); MEG; function magnetic resonance imaging (fMRI)

INTRODUCTION

Investigations of the neural correlates of the processing of musical structure are reviewed in this paper. In recent years, several studies investigated the neurocognition of music with electroencephalography (EEG).[1–7] In these studies, event-related brain potentials (ERPs) were calculated from the EEG. ERPs provide information about electric activity of cortical neurons as a response to an experimental stimulus,

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Ann. N.Y. Acad. Sci. 999: 15–28 (2003).
doi: 10.1196/annals.1284.002

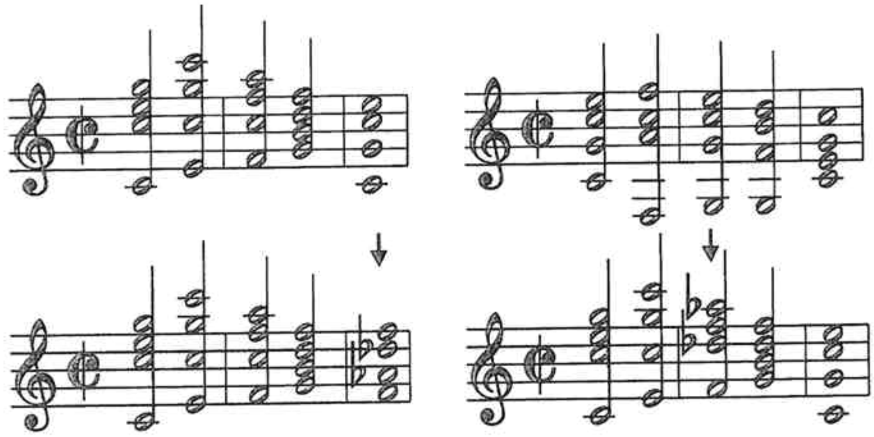

FIGURE 1. Chord sequences exclusively consisting of in-key chords (**a**), containing a Neapolitan sixth chord at the third position (**b**) and at the fifth position (**c**). To exclude the possibility that effects were due to the different interval structure of Neapolitan chords, Neapolitan and tonic chords were presented counterbalanced in root position, as sixth chords, and as six-four chords (in a strict sense, Neapolitans are sixth chords).

such as the presentation of a musical event. The temporal resolution of ERPs is usually in the millisecond range.[8]

In some of the aforementioned studies,[4,6,7] ERPs elicited by harmonically inappropriate (Neapolitan sixth) chords were compared to those elicited by harmonically appropriate tonic chords (FIG. 1). In these studies, chord sequences were presented to the participants, each sequence consisting of five chords, one sequence directly following the other. Sequences consisted mainly of in-key chords and were composed in a way that a musical context was built up towards the end of each sequence (FIG. 1, for examples). Twenty-five percent of the chord sequences contained a Neapolitan chord at the third position, and 25% a Neapolitan chord at the fifth position of the sequence. (For experimental reasons, Neapolitan chords were not always presented as sixth chords.) Neapolitan chords are a prominent stylistic element of major-minor tonal music in both classical and popular music (although Neapolitan chords usually occur in minor tonal environments).

The regularities according to which chord functions and harmonic relations are arranged within a major-minor tonal context have also been denoted as part of a *musical syntax*;[3,4,9–17] the dominant-tonic progression at the end of a harmonic sequence has especially been considered a basic syntactic structure of major-minor tonal music.[9,10,18] The term "musical syntax" does not imply that it is a linguistic syntax in musical terms; rather it points to the fact that music is structured according to complex regularities, a feature reminiscent of language. At the end of a harmonic progression, a tonic chord is the most regular chord function, especially when preceded by a dominant seventh chord. Thus, a Neapolitan chord presented instead of a tonic (after the presentation of a dominant seventh chord) violates the musical regularities, or musical syntax. For listeners familiar with the regularities of major-minor tonal music, the sound of a chord that violates musical regularities is perceived as unexpected.[12–15,18] Note that Neapolitan chords are classically used as a subdominant variation and that they often precede a dominant seventh chord. Thus, Neapolitan chords presented instead of a subdominant at the third position of the sequences (FIG. 1) violate the musical regularities to a smaller degree than do Neapolitans presented instead of a tonic at the end of the chord sequences.

BRAIN SIGNATURES OF MUSICAL SYNTAX

Several experiments have shown that Neapolitan chords elicit a relatively early electric brain response: a negative electric effect with right anterior scalp distribution (FIG. 2), the *early right anterior negativity* (ERAN). Like mismatch negativity (MMN,[19] which is known to reflect the automatic detection of irregularities on a sensory level in a stream of auditory information), the ERAN inverts polarity at mastoidal electrode sites when nose reference is used.[7] The ERAN is usually followed by a late frontal negativity, denoted as the *N5*. The amplitude of the ERAN is maximal around 190–250 ms; the N5 usually peaks around 500–550 ms. ERAN and N5 have been observed in both nonmusicians[4,7] and musicians.[6]

The ERAN is taken as a reflection of the violation of a musical sound expectancy. As just described, such an expectancy is generated according to the complex regularities of major-minor tonal music. We assume that nonmusicians acquire these regularities during exposure to major-minor tonal music in everyday life.[18] With respect to this, ERP effects suggest that even nonmusicians have a sophisticated (implicit) knowledge about the complex regularities of major-minor tonal music and that the acquisition of musical regularities as well as the processing of musical information according to these regularities is a general ability of the human brain.[4] The N5 is taken to reflect processes of subsequent musical integration,[4,6,7,17] an effect that will not be discussed in detail in this paper. (For a further description, see Koelsch *et al.*[20])

Interestingly, the degree of music-structural violation is reflected in an amplitude modulation of the ERAN (FIG. 2): Neapolitan chords presented at the fifth position (a position at which they are structurally highly inappropriate) elicit a larger ERAN compared to Neapolitans presented at the third position (where Neapolitans are less inappropriate).[4] This difference of the degree of music-structural violation is also reflected in behavioral discrimination performance: when participants are instructed to detect the Neapolitan chords, hit rates are higher for Neapolitans that are highly inappropriate than for Neapolitans that are fairly appropriate.[4]

FIGURE 2. Effects of processing musical violations. **(a)** Grand-average ERPs of Neapolitan and tonic chords at the fifth position. Neapolitan chords elicited an early right anterior negativity (ERAN) and a late bilateral negativity (N5). It is suggested that the ERAN reflects the violation of a musical sound expectancy and the N5 integration processes. **(b)** Grand-average ERPs of chords at the third (0–600 ms) and fourth position (600–1200 ms). Chords at the third position were either Neapolitan chords or in-key chord functions. Both ERAN N5 elicited by the Neapolitan chords were considerably smaller than those elicited by Neapolitans at the fifth position, indicating a processing of Neapolitan chords that was dependent on regularities of musical structure. (Reprinted with permission from Koelsch *et al.*[4])

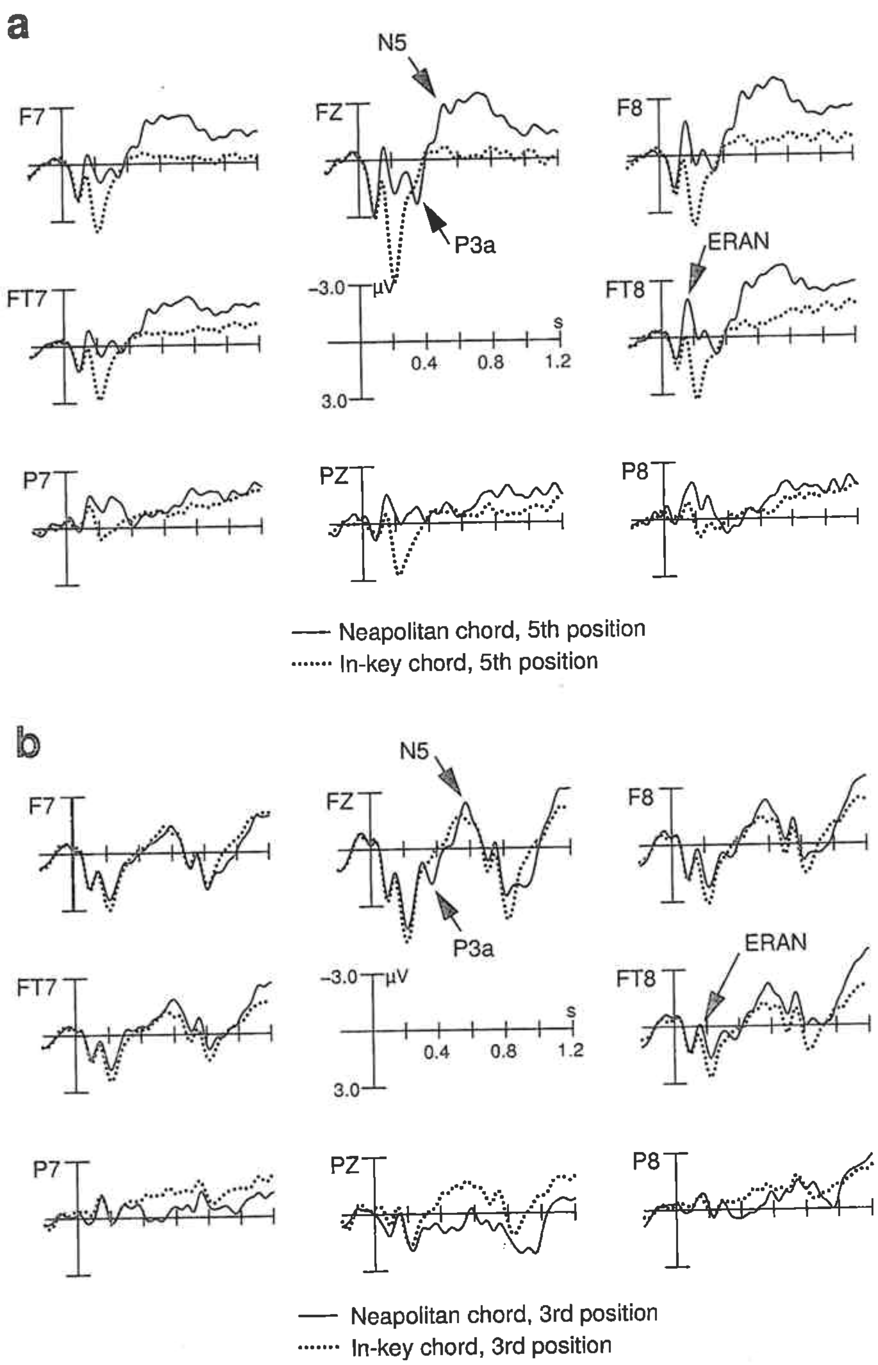

FIGURE 2. *See previous page for legend.*

MUSICAL VERSUS PHYSICAL IRREGULARITY DETECTION

Because Neapolitan chords introduce tones that have not been presented in the directly preceding chords (in C major, the out-of-key notes *a flat* and *d flat*), the structural inappropriateness of Neapolitans confounds with physical deviance. However, note that the physical deviance of the Neapolitans is virtually the same at positions three and five of the sequences, whereas the degree of music-structural violation is different between positions three and five of the chord sequences. Therefore, it seems plausible that the ERAN is partly overlapped by processes of physical irregularity detection (which operate independent of knowledge of music-syntactic regularities), but it is highly likely that the main contribution of the ERAN effect (especially when elicited at the fifth position) originates from neural processes connected to music-syntactic processing. A previous study[17] suggests that the amount of physical irregularity detection contributing to the ERAN is not larger than part of the early effect elicited by Neapolitan chords at the third position. Interestingly, frequency deviants presented with identical time course and probabilities as the Neapolitan chords elicit an MMN that does not differ in amplitude between positions three and five. This finding supports the notion that the amplitude difference of the ERAN elicited by Neapolitan chords at positions three and five is due to the difference in music-structural (in)appropriateness (see above).

To test the hypothesis that the ERAN can be elicited without the presence of a physical deviance, we constructed five-chord sequences (FIG. 3) in which the fourth chord was a dominant and the terminal chord either the tonic (i.e., a structurally regular chord function) or the dominant to the dominant (i.e., a structurally irregular chord function). Note, therefore, that in one sequence type the fourth chord was the dominant of the fifth chord, whereas in the other sequence type, the fifth chord was the dominant of the fourth chord. (The harmonic distance between the last two chords was, thus, always one fifth.) Moreover, the terminal tonic chord had no notes in common with the immediately preceding chord and three notes in common with the other three chords; the terminal dominant to the dominant had one note in common with the immediately preceding chord and four notes in common with the other three chords. If expectancies were generated on the basis of local feature processing and note (pitch) repetition effects, the terminal tonic would violate expectancies more than the terminal dominant to the dominant. On the other hand, if expectancies were generated on the basis of music-syntactic regularities, the dominant to the dominant would violate expectancies more than would the tonic.

Using this stimulus material, a study was conducted in which participants (none had participated in extracurricular music lessons or performances) were asked to press one button in response to the tonic and another in response to the dominant-to-dominant. Each sequence was presented randomly in another key and ended randomly with equal probability on either tonic or dominant-to-dominant (FIG. 3). Compared to the regular terminal chords, the music-structurally irregular chords elicited an ERAN (peaking around 200 ms), which was followed by an N2b-P3 complex (FIG. 3). Note that the N2b does not invert polarity at mastoidal sites, ruling out the possibility that the negativity around 200 ms is (purely) an N2b. Because the terminal dominant to the dominant represented a structural but not a physical irregularity, the data indicate that the ERAN can be elicited even without the presence of a physical deviance (and, thus, reflects the processing of a music-structural or music-

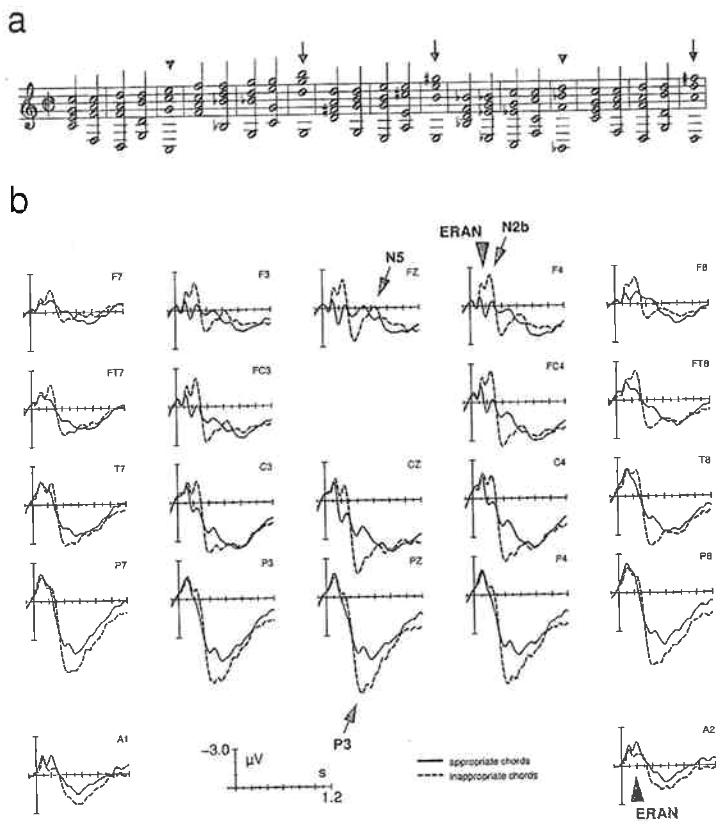

FIGURE 3. (**a**) Examples of chord sequences. *Short arrows* indicate the harmonically appropriate sequence endings (tonic chord), *long arrows* the inappropriate endings (dominant to dominant). Sequences were presented in direct succession, each sequence was presented randomly in a different tonal key, appropriate and inappropriate endings occurred with $P = 0.5$, and the order of the two sequence types was randomized. (**b**) Grand-average of ERP waveforms elicited by sequence endings (*solid line*, harmonically appropriate tonic; *dashed line*, harmonically inappropriate dominant to dominant). Compared to the appropriate chord functions, the inappropriate chord functions elicited an ERAN which inverted polarity at mastoidal sites (*short arrows*), followed by an N2b, a P3, and probably an N5.

syntactic irregularity). Notably, the data also indicate that the ERAN is not specific to the processing of Neapolitan chords.

Note, however, that both Neapolitan and dominant-to-dominant chords represent irregularities of (1) musical structure and (2) tonality (both chord types are out-of-key chords). It is therefore not yet clear if the ERAN can be elicited even without the presence of a violation of tonality. We addressed this issue in recent studies (unpublished data) and found that even in-key chord functions (such as submediants) elicit an ERAN, indicating that the ERAN is also present when a structural violation does not coincide with a violation of tonality.

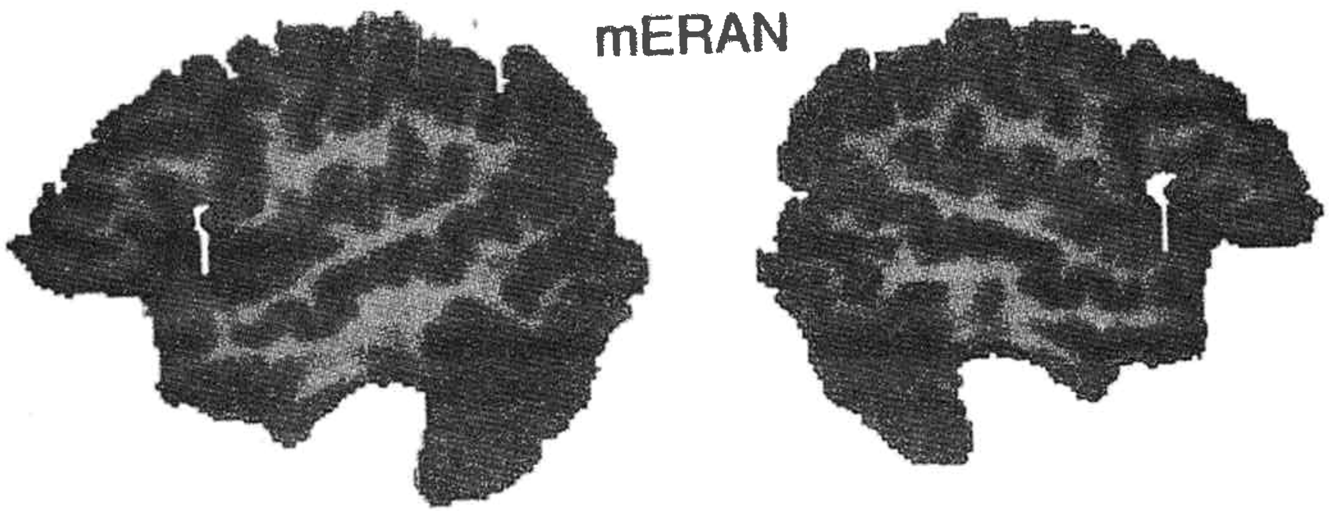

FIGURE 4. Grand average dipole solution (*white*) of the mERAN (from six subjects), from left and right sagittal views. Dipole solutions for the mERAN-effect (difference signals: tonic subtracted from deviants) refer to two dipole configurations (one dipole in each hemisphere). *Black disks* represent single subject solutions. In each hemisphere, a source was located in the frontal opercular cortex, areas known to be crucially involved in the processing of syntactic structure during language comprehension. (Adapted from Maess *et al.*[16])

ATTENTION AND INFLUENCE OF MUSICAL EXPERTISE

The ERAN can be elicited under preattentive listening conditions[7]: when participants read a book while chord sequences were presented, both ERAN and N5 were clearly present. In the second part of the same experiment, participants attended the musical stimulus and detected the inappropriate harmonies. In that part, the ERAN was only marginally larger than when the musical stimulus was ignored.

Recently, we found that the ERAN is larger in musicians than in nonmusicians,[6] reflecting that musicians, presumably because of their explicit knowledge about musical regularities and harmonic relations, are more sensitive to violations of musical structure.

SYNTAX IN MUSIC AND LANGUAGE

With magnetoencephalography (MEG), the main neural generators of the ERAN were localized in the inferior frontolateral cortex (inferior pars opercularis, in the left hemisphere part of *Broca's area*; FIG. 4).[16,21,22]

Interestingly, the ERAN is reminiscent of early anterior negativities that correlate with the early detection of an error in the syntactic structure of a sentence (usually observed with a maximum over the left hemisphere).[23,24] For example, the early left anterior negativity (ELAN)[24,25] has been observed in response to words with unexpected syntactic properties in sentences (phrase structure violations). Thus, both ERAN and ELAN are sensitive to violations of an expected structure; moreover, both ERAN and ELAN are negativities that are maximal around 200 ms, have a lateralized anterior scalp distribution, reflect fairly automatic processes, and receive contributions from generators located in the inferior frontolateral cortex.[22,24–26] The ELAN receives additional contributions from the planum polare, but the dipole solution of the MEG localizing the ERAN in the inferior frontolateral cortex[16] does not exclude that the ERAN also receives contributions from the (anterior) supratemporal cortex.

The similarities between ERAN and ELAN suggest that structural information of both music and language is processed by similar brain mechanisms. With respect to the similarities between ERAN, ELAN, and MMN, it was previously suggested that these ERP effects belong to a family of perisylvian negativities that mediate the processing of irregularities of auditory input[17] and that the neural generators of ELAN, ERAN, and MMN are part of a highly adaptive, perisylvian system of auditory information-processing that mediates the processing of single tones,[19,27] acoustic patterns,[28] phonemes,[29] tonal music,[4] and speech.[30]

Note that in a study by Patel *et al.*,[3] in which music and language processing was directly compared, both linguistic and musical structural incongruities elicited the same P600 (or LPC). Thus, it was suggested that the P600 probably reflects general knowledge-based structural integration processes during the perception of rule-governed sequences. Moreover, in that study the harmonically inappropriate chords elicited an ERP effect similar to the ERAN, denoted by Patel *et al.* as right anterotemporal negativity (RATN). This component was taken to reflect the application of music-specific rules, or probably music-specific working memory processes. In contrast to the ERAN, the RATN had a longer latency (around 350 ms), was

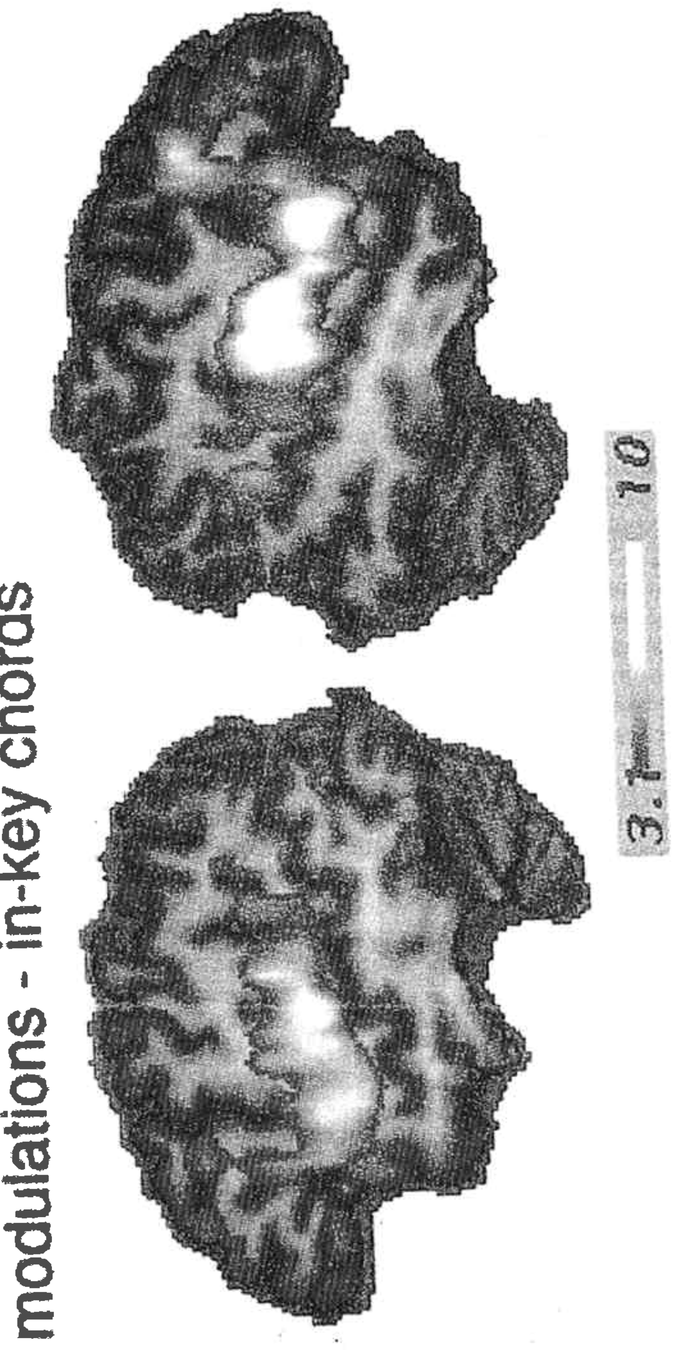

FIGURE 5. Statistical parametric maps (*z*-scores are indicated in the scale) of the contrast modulations versus in-key chords, mapped onto an individual brain. The panel shows views from left (Talairach coordinate $x = -50$) and right sagittal (Talairach coordinate $x = 46$).

observed only over the right hemisphere, and has so far only reportedly been elicited in musicians.

The MEG results (FIG. 4) have been supported by a study with functional magnetic resonance imaging (fMRI).[31] As in the MEG study, the inferior frontolateral cortex was activated during the processing of irregular chord functions (FIG. 5). Interestingly, besides inferior frontolateral cortical areas, posterior temporal areas (in the left hemisphere often referred to as Wernicke's area) are activated bilaterally by the processing of structurally inappropriate musical events. Note that the inferior frontolateral and the posterior temporal cortex are crucially involved in the perception of language.[32–34] The fMRI results concur with findings that indicate considerable overlap of neural structures and processes underlying the perception of music and language.[3,4,16,21,35–39]

In a recent fMRI experiment with a sparse temporal sampling technique we presented Neapolitan chords as structurally inappropriate musical events (as in the aforementioned previous EEG and MEG studies).[40] In that study, activations of the inferior frontolateral cortex as well as some posterior temporal activations were replicated, but no activation of Heschl's gyrus was found. This finding indicates that possible contributions of physical irregularity detection (as reflected electrically in the MMN) to the ERAN are only marginal and that the ERAN originates from different cortical regions than the physical MMN (e.g., frequency MMN): whereas the ERAN appears to receive main contributions from areas located in the inferior frontolateral cortex (and probably the anterior part of the superior temporal gyrus, with no contribution from primary auditory areas), the (physical) MMN receives its main contributions from areas located within or in the close vicinity of primary auditory areas, with additional contributions from anterior frontal cortical areas.

However, given the broadening of the MMN framework, which summarizes perisylvian negativities that mediate the fast and automatic processing of auditory irregularity detection, the ERAN may be regarded as an MMN elicited by the highly abstract feature "music-syntactic appropriateness." With respect to this, we suggested that the ERAN may be understood as a "music-syntactic MMN."[6,7,41]

The localization of (language-) syntactic processes using fMRI suggests involvement of the anterior portion of the left superior temporal gyrus and the frontal operculum adjacent to BA44.[26,42] In a recent fMRI experiment that used the same auditory sentence material as in a previous MEG study,[22] some areas increased their activation as a function of syntactic violation. These are the anterior portion and the posterior portion of the left superior temporal gyrus and the frontal operculum.[43] The anterior portion of the superior temporal gyrus and the frontal opercular activation was also observed in an fMRI study presenting sentences in which all content words were replaced by pseudowords.[44] Thus, it appears that the posterior superior temporal gyrus activation reflects the integration of semantic and syntactic information and that the anterior portion of the superior temporal gyrus together with the inferior frontal region supports syntactic processes as such.

PROCESSING STUCTURAL INFORMATION IN CHILDREN

To investigate developmental aspects of music processing, we conducted the EEG experiment with Neapolitan and in-key chords,[4,6] measuring two groups of children:

9- and 5-year-olds (children who had not received any formal musical training). The harmonies were task irrelevant, and children were asked to respond to infrequently occurring chords played with an instrumental timbre deviating from the standard piano timbre. As in adults, Neapolitan chords presented at the fifth position elicited distinct early and late ERP effects in both 5- and 9-year-old children: an earlier negativity, which was maximal around 320 ms and therefore around 120 ms later than that in adults, and a later negativity, the N5, maximal around 550 ms.

The finding that in both age groups the ERPs of Neapolitan chords differed from those elicited by structurally appropriate chords indicates that already the 5-year-old children processed the chords according to their harmonic appropriateness. As did adults, children showed a remarkable amplitude reduction of ERP effects for Neapolitan chords at the third position, suggesting that already 5-year-old children processed the musical stimulus according to regularities of "classical" major-minor tonal music, which are described by the theory of harmony.

As these regularities have previously been denoted as part of a musical syntax (see above), the findings suggest that already 5- and 9-year-old children have an (implicit) knowledge of musical syntax, that is, the complex regularities of tonal music.

Because children had no special musical expertise, the findings support the hypothesis that the acquisition of knowledge about musical regularities and the processing of musical information according to this knowledge is a general ability of the human brain, which is already present at the age of 5 (if not earlier). At this age, children participating in the study had been exposed in everyday life to major-minor tonal music, that is, the regularities underlying the music of their culture.

The described effects were present although the Neapolitan chords were task irrelevant, suggesting that children process harmonic relations and musical structure fairly automatically, that is, even when they do not specifically attend harmonies. (This finding concurs with the discovery that the ERAN can be elicited preattentively in adults.[7])

The observation of sophisticated musical abilities in children corresponds with the observation that musical elements of speech play an important role in the acquisition of language; it has been hypothesized that music and speech are intimately connected in early life,[45,46] that musical elements pave the way to linguistic capacities earlier than phonetic elements,[47] and that melodic aspects of adult speech to infants represent the infant's earliest associations between sound patterns and meaning[48] as well as between sound patterns and syntactic structure.[49–51] With this respect, it is also interesting to note that the ERAN can already be observed at the age of 5 (presumably even earlier), whereas the fast and automatic processing of syntactic violations in language as reflected in the ELAN (see above) becomes observable around the age of 9–10 (unpublished data from A. Hahne and A.D. Friederici). Thus, the fast and automatic processes of structure analysis during the comprehension of complex regularity-based auditory information (as reflected in early anterior negativity) appear to be employed earlier for musical than for linguistic information. That is, it appears that children do not learn language before music, but music before language, supporting the notion that musical elements of speech (such as prosody) play a crucial role in the infant's earliest associations between sound patterns and syntactic structure,[49–51] and thus for the acquisition of language.[45–48,50,51]

In conclusion, data obtained with different investigation methods and from different subject groups indicate that musical structure can be processed by brain mechanisms that operate (a) fairly automatically, (b) with a latency around 180 ms, and that (c) mainly originate from the frontal cortex (probably with contributions from anterior temporal lobe structures). These brain mechanisms can be observed in non-musicians, musicians, adults, and children, and these mechanisms appear to be similar, and partly overlapping, with the mechanisms that process structure during language comprehension. Results indicate that the ability to acquire (implicit) knowledge about musical regularities and the ability to process musical information according to these regularities is a general ability of the human brain. This ability appears to be important for the acquisition of language.

NOTE: Examples of the stimuli are available at http://www.stefan-koelsch.de

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