

Electric brain responses to inappropriate harmonies during listening to expressive music

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Abstract

Objectives: Recent studies with event-related brain potentials (ERPs) investigating music processing found (early) negativities with right-hemispheric predominance as a response to inappropriate harmonies within sequences of chords. The stimuli used in those studies were fairly artificial in order to control the experimental factors (e.g. variations in tempo and loudness were eliminated). This raises the question of whether these ERPs can also be elicited during listening to more naturalistic stimuli.

Methods: Excerpts from classical piano sonatas were taken from commercial CDs and presented to the participants while recording the continuous electroencephalogram. Expected chords and unexpected (transposed) chords were presented at the end of chord-sequences.

Results: Unexpected chords elicited a negativity which was maximal around 250 ms, visible over both hemispheres, and preponderant over right temporal leads.

Conclusions: The found negativity is strongly reminiscent to both early right anterior negativity and right anterior-temporal negativity, suggesting that cognitive processes underlying these ERP components are not only elicited with fairly artificial experimental stimuli but also when listening to expressive music. © 2002 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Auditory processing; Music; Electroencephalogram; Early right anterior negativity; Right anterior-temporal negativity; P3; N5; Late positive component

1. Introduction

The investigation of the cognitive processing of complex rule-based auditory information is a major aspect of brain research. Numerous studies investigated this field with linguistic stimuli, and recently, this field was considerably expanded by the investigation of music processing. Studies with electroencephalography (EEG) revealed that harmonically inappropriate chords presented within a sequence of chords elicit brain responses with a latency of around 180–400 ms that are maximal over the right hemisphere (Patel et al., 1998; Koelsch et al., 2000b, 2001a,b, 2002).

In the study from Patel et al. (1998), musicians were presented with chord sequences that were written in a popular style, sequences varying in their length from 7 to 12 chords (duration was on average 6 s). Harmonically inappropriate chords elicited a right anterior-temporal negativity (RATN), which was observed only over the right hemisphere, had a latency of around 350 ms, and did not show

to be sensitive to the degree of violation. The RATN was taken to reflect the application of music-syntactic rules (and possibly working memory operations), and followed by a parietal positivity with a latency of around 600 ms. This positivity was suggested to reflect knowledge-based structural integration during the perception of rule-governed sequences.

In the studies from Koelsch et al. (2000b, 2001a,b, 2002), chord-sequences (each consisting of 5 chords) were composed in a classical style (and according to the rules of part-writing) and presented to both non-musicians (Koelsch et al., 2000b, 2001b, 2002) and musicians (Koelsch et al., 2001a). Harmonically inappropriate chords elicited an early right anterior negativity (ERAN) that was clearly visible over both hemispheres, although right preponderant, and which had a maximal amplitude around 200 ms. The ERAN has been shown to be: (a) sensitive to the degree of violation; (b) connected to behavioral discrimination performance and probability (Koelsch et al., 2000b); (c) elicited under both attentive and pre-attentive listening conditions (Koelsch et al., 2002); (d) larger in musicians compared to non-musicians (Koelsch et al.,

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Fig. 1. Examples of stimuli, taken from a recording of a piano sonata from Haydn (Hoboken XVI:48), the two excerpts are identical except that the chord indicated by the grey-shaded area is harmonically appropriate in example (a); and inappropriate in example (b). The inappropriate (transposed) chord is a consonant chord, it is only the harmonic relation to the preceding musical context that makes this chord harmonically inappropriate.

2001a); and (e) shown to receive its main contributions from generators located in Broca's area and its right hemisphere homologue (Koelsch et al., 2000c; Maess et al., 2001). The ERAN is interpreted as reflecting the violation of a musical sound expectancy, the musical expectancies being generated based on (implicit) knowledge about the complex regularities of (major-minor) tonal music, that is based on (implicit) knowledge about a musical syntax. The ERAN is usually followed by a frontal negativity which is maximal around 400–600 ms. This negativity was hypothesized to reflect processes of harmonic integration and termed 'N5'.

In contrast to 'real music', however, the stimuli presented in the studies from Patel et al. (1998), Koelsch et al. (2000b, 2001a,b, 2002), and Maess et al. (2001) were played by a computer with no dynamics and agogics, i.e. with no variations in tempo or loudness. Moreover, the stimuli of the studies from Koelsch et al. (2000b, 2001a,b, 2002) and Maess et al. (2001) had a repetitive character, because each chord-sequence comprised 5 chords, and each sequence directly followed the other.

It is hence unclear whether (early) negativities as a response to musical violations are only elicited by fairly artificial experimental stimuli, or whether they are also present during listening to 'real', i.e. expressive music. In order to investigate brain responses to more naturalistic stimuli, the present study employed excerpts of piano sona-

tas from Beethoven, Haydn, Mozart, and Schubert; the excerpts were recorded from commercially available CDs. Two stimulus-types were presented: first, sequences containing a progression of harmonies that ended with a harmonically related (and thus expected) chord (Fig. 1a), and second, sequences in which a progression of harmonies was terminated by a harmonically unrelated (and thus unexpected) chord (Fig. 1b).

The expected endings were always so called 'tonic' chords. The tonic chord is harmonically most closely related to a sequence of preceding (in-key) chords, and the chord-function of the tonic is highly appropriate at the end of a progression of harmonies (Schönberg, 1969). From a music psychological perspective, chords that are harmonically closely related to a preceding harmonic context, and functionally highly appropriate, are perceived as expected; harmonically unrelated and functionally inappropriate chords are perceived as unexpected (Krumhansl et al., 1982; Krumhansl and Kessler, 1982; Bharucha and Krumhansl, 1983; Bharucha and Stoeckig, 1987; Bigand and Pineau, 1997; Tillmann et al., 1998; Bigand et al., 1999). The specificity of harmonic expectancies correlates with the degree of harmonic relatedness and functional appropriateness described by music theory (Krumhansl et al., 1982).

In the present study, the sequences with unexpected endings were the same sequences as those with expected

endings, except that the expected tonic chord was made harmonically unrelated by shifting the original chord one semi-tone upwards (Fig. 1b). This experimental manipulation was employed in order to guarantee that both sequence-types (sequences terminated by an expected chord, and sequences terminated by an unexpected chord) did only differ with respect to their terminal chords. It is very important to note that the transposed chords themselves remained perfectly consonant chords, it was only the incompatibility with a preceding musical context that made the transposed chords harmonically inappropriate: the transposed chords were harmonically only distantly related to the preceding chords, and had (due to the transposition) an inappropriate chord function. Note that it is aesthetically appealing for composers to violate the expectancy of listeners, e.g. by terminating a sequence with an harmonically unrelated (and thus unexpected, or surprising) chord. Moreover, the transposed chords are reminiscent of augmented 6-5 chords (although without augmented sixth), which are a prominent stylistic element of classical music. Thus, the transposed chords were not very salient and not easily to detect for the participants.

The shift of one semi-tone upwards corresponds to a harmonic distance of 5 fifths (in the sense of the circle of fifths, for explanations see, e.g., Krumhansl and Kessler, 1982; Patel et al., 1998). This harmonic distance equals the most distant chords in the study from Patel et al. (1998), and the Neapolitan chords of the studies from Koelsch et al. (2000b, 2001a,b, 2002) and Maess et al. (2001), enabling a comparison of results between those and the present study.

In summary, the present study investigates with expressive music whether harmonically inappropriate (transposed) chords elicit brain responses similar to those observed in previous studies with fairly artificial musical stimuli. Subjects were 'non-musicians' in order to enable a broad generalization of results.

2. Methods

2.1. Subjects

A total of 18 subjects (right-handed and normal hearing, aged 19–28 years, mean 22; 3, 9 females) participated in the experiment. All participants were 'non-musicians', i.e. they had no special musical expertise or education (besides normal school education).

2.2. Stimuli

Musical excerpts (30) were chosen from piano-sonatas from Haydn (5 excerpts), Mozart (5), Beethoven (15), and Schubert (5), and recorded from commercially available CDs. Most of the excerpts were chosen from Beethoven sonatas because the transposed chords came closest to Beethoven's style of composition. Duration of excerpts

differed between 15 and 45 s. Excerpts were chosen in a way that a cadence (i.e. a sequence consisting of in-key chords only) at the end of the excerpt was terminated by an (expected) tonic chord. Each excerpt was duplicated in order to transpose the expected tonic chord one semi-tone upwards, corresponding to a distance of 5 fifths (in the sense of the circle of fifths) compared to the tonic chord (Fig. 1). The transposition was made electronically using Cool-Edit 2000. Transposed chords differed from original chords only with respect to their pitch height. All stimuli were presented twice during an experimental session in order to increase the signal-to-noise ratio. Examples of the stimuli are available at <http://www.stefan-koelsch.de>.

2.3. Procedure

Participants were informed about the presence of transposed chords. An example of a sequence without a transposed chord and two sequences with a transposed chord were presented to each participant before starting the EEG-measurement. Participants were asked to indicate after each trial whether or not the previous sequence contained a transposed chord by pressing a response button (time for response was 4 s). They were instructed to look at a fixation cross. The duration of an experimental session was approximately 40 min.

2.4. EEG measurements

Measurements were performed in an acoustically and electrically shielded room. The EEG was recorded with Ag-AgCl Electrodes from 49 scalp locations of the extended 10–20-system (Sharbrough, 1991), referenced to the left mastoid; sampling rate was 250 Hz (30 Hz low-pass). After the measurements, EEG-data were referenced off-line to the algebraically mean of both mastoid electrodes in order to guarantee that a lateralization of effects could not be due to the placement of the reference-electrode. Besides the EEG, horizontal and vertical electro-oculograms (EOG) were recorded (each EOG bipolarly). For elimination of artifacts caused by eye-movements, EEG-data were rejected off-line from the raw EEG whenever the standard deviation within any 200 ms interval exceeded 30 μ V in the vertical, or 30 μ V in the horizontal EOG. For elimination of artifacts caused by drifts or movements, EEG-data were rejected off-line from the raw EEG whenever the standard deviation within any 600 ms interval exceeded 25 μ V at either of all electrodes. Rejections were visually inspected and controlled by the first author.

2.5. Data-analysis

In order to evaluate the amplitudes of the ERPs statistically, 4 regions of interest (ROIs) were computed by calculating the mean amplitudes for the electrodes of each ROI: left anterior (F3, FC3, F5, FC5), right anterior (F4, FC4, F6, FC6), left posterior (P3, P5, CP3, CP5), and right posterior

(P4, P6, CP4, CP6). Variances of ERPs were analyzed by repeated measures analysis of variances (ANOVAs) as univariate tests of hypotheses for within subjects effects. One ANOVA was conducted with factors chord-type (two levels: in-key \times transposed chords), anterior-posterior distribution (two levels: anterior \times posterior ROIs), and lateralization (two levels: left \times right ROIs). Another ANOVA was conducted with factors chord-type, anterior-posterior distribution, and time-window (two levels: 350–450 versus 500–600 ms). Moreover, a two-tailed one sample *t* test was conducted comparing the amplitudes of ERPs elicited by in-key versus transposed chords from frontal and anterior-frontal electrodes (mean values of F3, F5, F7, FZ, F4, F6, F8, AF7, AFZ, AF8). For presentation purposes only, averaged data were filtered with a 10 Hz low-pass filter (41 points, FIR).

3. Results

Participants detected on average only 39.6% of the transposed chords, indicating that the transposed chords were not very salient and thus not easy to detect. This finding might indicate that some of the transposed chords were perceived as stylistic element, rather than as experimental manipulation.

The ERP data indicate that transposed chords elicited compared to in-key chords a negativity in the range of 180–350 ms which was maximal at 250 ms after the onset of the transposed chords (Fig. 2). This effect was broadly distributed over the scalp, maximal over centro-temporal leads, and preponderant over the right hemisphere. An ANOVA with factors chord-type (in-key versus transposed chords), anterior-posterior distribution (anterior \times posterior ROIs), and lateralization (left \times right ROIs) for a time-window from 200 to 320 ms revealed an effect of chord-type ($F(1,16) = 5.71$, $P < 0.05$, indicating that the amplitudes of brain responses differed between unexpected and expected chords), and an interaction between factors chord-type and lateralization ($F(1,16) = 5.22$, $P < 0.05$, indicating that the effect elicited by unexpected chords differed in amplitude between the two hemispheres).

The negative effect was followed by positive potentials which began at frontal leads around 320 ms, and at parietal leads around 370–400 ms. These potentials were between 350 and 450 ms anteriorly maximal, and in the later latency windows (from around 500 ms on) posteriorly maximal (Fig. 2). An ANOVA with factors chord-type, anterior-posterior distribution, and time-window (350–450 \times 500–600 ms) revealed an effect of chord-type ($F(1,16) = 14.82$, $P < 0.002$) and an interaction between factors chord-type, anterior-posterior distribution, and time-window ($F(1,16) = 23.8$, $P < 0.0002$, indicating that the effect of unexpected chords differed in its scalp distribution between the two time-windows).

At frontal and anterior-frontal electrodes, the positivity was followed by a negativity which was maximal around

800–1200 ms (Fig. 2). A two-tailed one sample *t* test comparing the amplitudes of ERPs elicited by in-key versus transposed chords from frontal and anterior-frontal electrodes (mean values of F3, F5, F7, FZ, F4, F6, F8, AF7, AFZ, AF8) in the time-window from 800 to 1200 ms revealed a difference between the ERPs ($F(1,16) = 4.85$, $P < 0.05$).

4. Discussion

Harmonically inappropriate (transposed) chords evoked electric brain activity in the range from around 180 to 350 ms which had a negative polarity, was broadly distributed and maximal over the right hemisphere. This effect is strongly reminiscent to both ERAN (Koelsch et al., 2000b, 2001a,b, 2002) and RATN (Patel et al., 1998), which are also elicited by harmonically inappropriate chords, and also negativities which are predominant over the right hemisphere (see also below). The present results demonstrate that (early) right-predominant negativities in response to inappropriate harmonies are not only elicited with rather artificial experimental stimuli, but also when preceded by expressive music, i.e. as a brain response during listening to fairly naturalistic musical stimuli. Although the transposed chords were an experimental manipulation, the behavioral results suggest that this manipulation was not very salient and presumably often rather perceived as stylistic element (note that the transposed chords were from a music-theoretical perspective reminiscent of augmented 6-5 chords which are a prominent stylistic element of classical music).

With respect to the ERAN, the negativity elicited in the present study is particularly similar in its time-course; moreover, the present negativity is, as the ERAN, visible over both hemispheres. The maximum over temporal leads is not typical for the ERAN (which is usually maximal over frontal leads), although this scalp distribution has already been reported for the ERAN (see experiment 4 of Koelsch et al., 2000b). With respect to the RATN, the present negativity is particularly similar in its scalp distribution, although the RATN has been reported to be visible only over the right hemisphere, whereas the present effect is visible over both hemispheres. Moreover, the RATN has a latency of around 350 ms, whereas the present negativity is maximal around 250 ms. Also note that the ERAN was in previous studies elicited in non-musicians, as in the present experiment, whereas the RATN has so far only been shown to be present in musicians.

Due to the strong similarities of the observed effect with both ERAN and RATN, it is difficult to decide which of the two components was elicited in the present experiment, especially since the RATN has so far been reported in only one study. However, it seems plausible that either both components (ERAN and RATN), or processes very similar to both ERAN and RATN were elicited in the present experiment. Note that the brain mechanisms underlying both ERAN and RATN seem to have a similar func-

tional significance (see Section 1), and that it still remains to be clarified which parameters modulate both time-course and scalp distribution of these music-related negativities.

Note that the present negativity is not a ‘classical’ frequency mismatch negativity (MMN), since the transposed chords were not preceded by physically identical

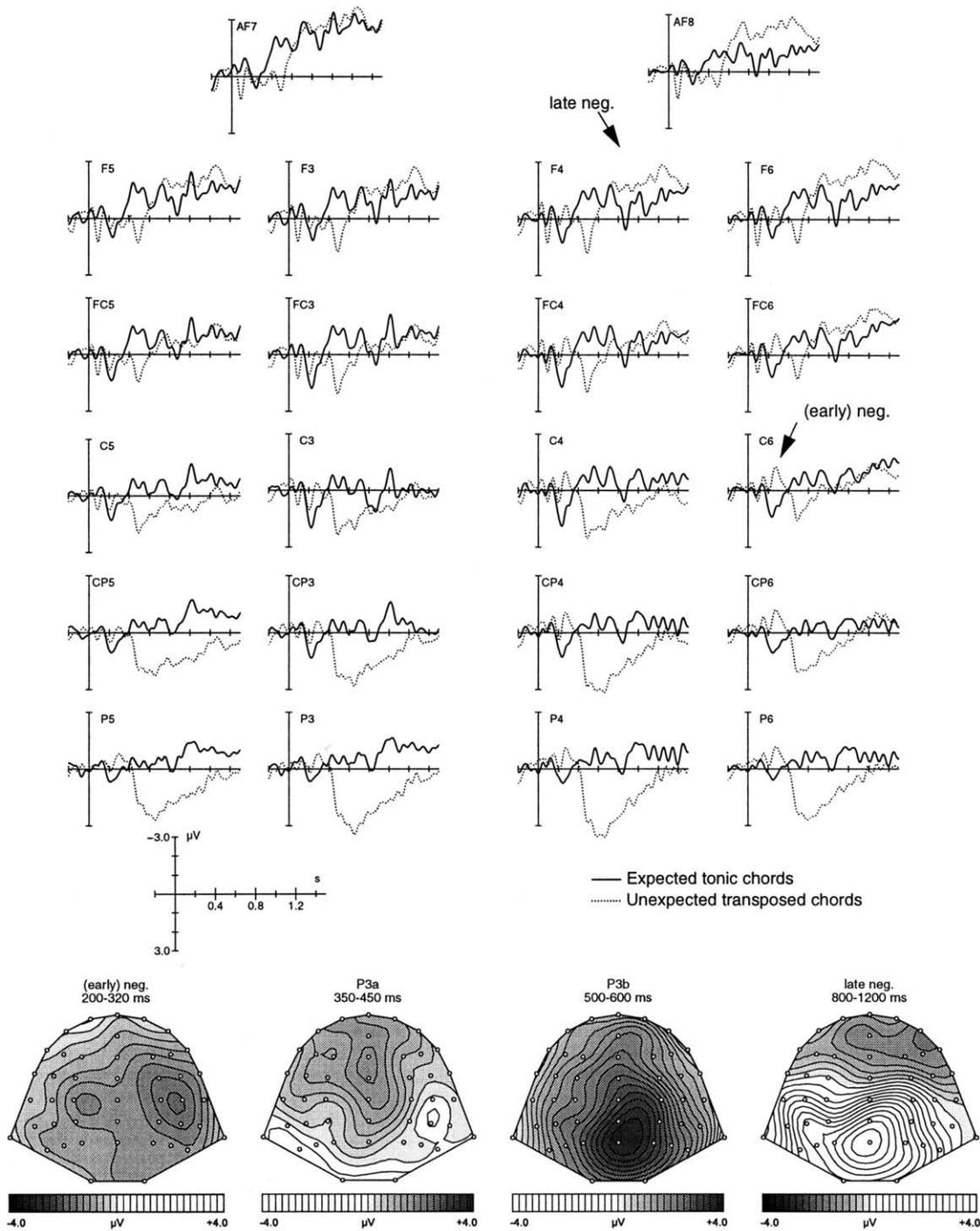


Fig. 2. Top: Grand-average ERP waveforms to expected tonic chords (solid line) and unexpected transposed chords (dotted line). Transposed chords elicited a broad (early) negativity (indicated by the arrow over the C6-electrode) which was followed by positivities in the range from 320 to 1500 ms. Around 800–1200 ms a late frontal negativity is visible (indicated by the arrow over the F4-electrode). Bottom: Potential maps of the effects elicited by the transposed chords (difference ERPs: expected subtracted from transposed chords, view from top, nose is upwards). In the range around 200–320 ms, the early negativity had a maximum over centro-temporal leads of each hemisphere (left). The negativity was followed by a positivity which had a frontal distribution around 350–450 ms (middle-left, grey-scaled areas indicate positive potentials, white areas indicate negative potentials), and a late positivity from around 500 ms on which was parietally maximal (middle-right). The late negativity was frontally maximal (right, grey-scaled areas indicate negative potentials, white areas indicate positive potentials).

standard chords (Näätänen, 1992; Schröger, 1998; Kujala et al., 2001; Schröger et al., 2000; Tervaniemi et al., 1999; Escera et al., 2000). Moreover, it is interesting to note that the effect observed was not elicited in a repetitive auditory environment, indicating that (early) negative effects as a response to harmonically inappropriate chords can not only be elicited in the repetitive environment of classical auditory ‘oddball’ paradigms.

Moreover, it is highly unlikely that the early-negativity elicited in the present study is just due to a greater ‘sensory dissonance’ of transposed chords, i.e. due to the fact that the transposed chords shared less component tones (or overtones) with the preceding chords compared to the expected tonic chords (Schmuckler, 1989; Parncutt, 1989): In the studies from Koelsch et al. (2000b, 2001a,b, 2002) and Maess et al. (2001) the different size of amplitudes of the ERAN elicited by Neapolitan chords at different positions within chord sequences was not dependent on the degree of ‘sensory dissonance’, because the ‘sensory dissonance’ was fairly well balanced between the different positions at which Neapolitans were presented. Instead, the amplitude of the ERAN was mainly dependent on the degree of harmonic appropriateness of Neapolitans, which varied between the different positions at which the Neapolitans were presented. Also note that effects of ‘sensory dissonance’ within a musical context have been reported to elicit mainly later positive potentials (Regnault et al., 2001).

Thus, the early negativity elicited in the present study is, as ERAN and RATN, taken to reflect the violation of the complex regularities of (classical major-minor tonal) music. The arrangement of chord functions and harmonic relations in classical Western European tonal music follows regularities that are described by music theory and have been denoted as ‘musical syntax’ Swain (1997); Patel et al. (1998); Maess et al. (2001). The musical syntax was violated in the present study when a harmonically unrelated chord was presented instead of a tonic chord. Note that the ability of listeners to expect specific musical events according to musical regularities, and to detect violations of harmonic expectancies within a musical sequence has been taken as a reflection of a music-syntactic processing (Swain, 1997; Krumhansl and Kessler, 1982; Bharucha and Krumhansl, 1983; Bharucha and Stoeckig, 1986).

With this respect, it is interesting to note that the ERAN is reminiscent of the early *left* anterior negativity (ELAN, see Hahne and Friederici, 1999; Friederici, 1998), a similar but often left-lateralized effect observed in response to words with unexpected syntactic properties in sentences (phrase structure violations). ERAN and ELAN are similar with respect to: (a) polarity; (b) time course (both are maximal around 200 ms); (c) the lateralized anterior scalp distribution; (d) their neural generators (both components receive contributions from Broca’s area, although additional contributions from the planum polare have been reported for the ELAN, cf. Friederici et al., 2000; Maess et al., 2001); and (e) their sensitivity to violations of expected structure. The

similarities between ERAN and ELAN have been taken to support the hypothesis that the processing of syntactic incongruities in music and language relies on similar, if not partially the same, neural mechanisms (Maess et al., 2001).

Because of the similarities between ERAN, RATN, MMN, and ELAN, these ERP components have been suggested as reflections of a highly adaptive, peri-sylvian system of auditory information processing (Koelsch et al., 2002, 2001b), comprising the processing of single tones (Näätänen, 1992; Schröger, 1998), acoustic patterns (Schröger, 1994), phonemes (Näätänen et al., 1997), tonal music (Koelsch et al., 2000b), and speech (Friederici, 1998). The early negativity elicited in the present experiment also appears to be part of this system, being most reminiscent to the ERAN.

The (early) negativity was followed by two positivities, an earlier one being frontally maximal (around 350–450 ms), and a later one with a parietal maximum (from around 500 ms on). The positivities are strongly reminiscent to the P3a and the P3b, with respect to both time-course and scalp-distribution. Hence, the earlier positivity seems to reflect attentional processes elicited by the unexpected transposed chords (Näätänen, 1992; Ritter and Ruchkin, 1992), whereas the later positivity presumably reflects the decisional processes following the detection of the target chords (Näätänen, 1992; Pritchard, 1981). However, the later positivity is fairly tonic (lasting up to 1500 ms after the onset of the deviant chord), and thus also reminiscent, at least in its later time-window, to the P600 described by Patel et al. (1998). This music-related late positivity has previously also been denoted as the late positive component (LPC, Besson and Faita, 1995; Regnault et al., 2001).

The P600, or LPC, is taken to reflect structural integration during the processing of rule-based sequential information (Patel et al., 1998). Interestingly, the P600 elicited by musical stimuli has been reported to be statistically indistinguishable from the P600 elicited by linguistic structural incongruities. This finding was taken to indicate that the neural mechanisms underlying the generation of the P600 are not only activated by the processing of language, but also by the processing of music (Patel et al., 1998; Patel, 1998). With respect of similarities between music and language processing, it is interesting to note that the hypothesis of shared neural circuits underlying the generation of music- and language-related ERP components such as ERAN/ELAN, or P600, is supported by the findings that brain structures involved in the processing of language also play an important role for the processing of music (Platel et al., 1997; Liegeois-Chauvel et al., 1998; Peretz et al., 1994; Zatorre et al., 1994; Wallin et al., 2000; Maess et al., 2001; Koelsch et al., 2000a).

In a similar time-window, i.e. around 800–1200 ms, a late negativity was present in the ERPs of transposed chords that is reminiscent to the ‘N5’. The N5 is an ERP-wave taken to reflect processes of harmonic integration (Koelsch et al.,

2000b), in analogy to the N400 which reflects processes of semantic integration during the perception of language (for review see Friederici, 1998). However, due to its latency and pre-frontal maximum, the late negativity observed in the present study is not regarded as an N400.

Importantly, with respect to the similarities between the effects observed and ERAN, RATN, P600/LPC, and N5, the present results indicate that these components are not only elicited by fairly artificial experimental stimuli, but that they can also be evoked during listening to expressive music (the LPC has already been shown to be elicited by naturalistic, although one-part, stimuli, see Besson et al., 1998). The fact that all these components were elicited in the present experiment, but only few of them in the particular experimental settings of previous studies, might point to the fact that expressive music activates several processes to a higher degree than experimental stimuli which are often designed in order to investigate only a particular aspect of music processing.

Note that subjects of the present study were non-musicians, enabling to a broad generalization of results. With respect to a possible influence of expertise on the processes observed in the present study, it is plausible to assume that the early negativity would be larger in musical experts, as a recent study revealed that the ERAN is larger in musical experts compared to novices (Koelsch et al., 2001a). The finding of a larger ERAN in experts was interpreted as a reflection of a more specific cognitive representation of harmonic relations and musical syntax in highly trained musicians.

5. Conclusion

The present study aimed at investigating the processing of complex regularity-based auditory stimuli in a non-linguistic domain. Harmonically inappropriate chords presented within a sequence of expressive music (music played with variations in tempo and loudness) elicited an (early) negativity which was maximal over temporal leads, predominant over the right hemisphere, and reminiscent to the ERAN and the RATN. Results thus suggest that these ERP-components are not only elicited with rather artificial stimuli, but also present when listening to naturalistic musical stimuli. The findings justify those experimental settings in which certain aspects of music processing are particularly investigated with the ERAN and the RATN (leading to the exclusion of factors like dynamics and agogics and to stimuli that are less naturalistic than expressive music). The reminiscence of the later positivity to the P600/LPC, and the reminiscence of the late negativity with the N5 might suggest that a similar conclusion also holds for these ERP components. Note that in the present study 'non-musicians' showed distinct brain responses to harmonic incongruities, indicating an (implicit) knowledge of the participants about the regularities of classical major-minor tonal music.

Note: Examples of the stimuli and full color maps are available at <http://www.stefan-koelsch.de>.

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