Amygdala activity can be modulated by unexpected chord functions during music listening

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Numerous earlier studies have investigated the cognitive processing of musical syntax with regular and irregular chord sequences. However, irregular sequences may also be perceived as unexpected, and therefore have a different emotional valence than regular sequences. We provide behavioral data showing that irregular chord functions presented in chord sequence paradigms are perceived as less pleasant than regular sequences. A reanalysis of functional MRI data showed increased blood oxygen level-dependent signal changes bilaterally in the amygdala in response to music-syntactically irregular (compared with regular) chord functions. The combined data indicate that music-syntactically irregular events elicit brain activity related to emotional processes, and that, in addition to intensely pleasurable music or highly unpleasant music, single chord functions can also modulate amygdala activity. *NeuroReport* 19:1815–1819 © 2008 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

A number of previous functional neuroimaging studies on the processing of musical syntax have used chord sequences containing chord functions that were harmonically either regular or irregular [1–5] (for studies with melodies see e.g. [6,7]). These studies consistently showed involvement of inferior fronto-lateral (sometimes along with anterior superior temporal) cortex to be involved in the syntactic processing of chord functions. However, it is plausible to assume that irregular musical events (such as music-syntactically irregular chord functions) not only engage neural mechanisms underlying the processing of music-syntactic information, but that such chords also give rise to emotional responses: In his classic book on music and emotion, Leonard Meyer [8] theorized that listeners often have (implicit) expectations of what will happen in the music and, depending on whether these expectations are fulfilled or not, experience relaxation, or tension and suspense. Thus, according to Meyer [8], music-syntactically unexpected chords may lead to a sensation of surprise or suspense.

Several decades later, Meyer's theory received support from empirical data: it was found, for example, that new or unexpected harmonies evoke shivers, that the perception of irregular (i.e. unexpected) chord functions leads to an increase of perceived tension, and that the perception of tension is linked to emotional experience during music listening (reviewed in Ref. [9]). Moreover, empirical studies provided a direct test of Meyer's theory, investigating the role of music-specific expectations in the generation of emotional responses in the listener [9,10]. In these studies, unexpected chord functions elicited increased skin conductance responses, and behavioral measures indicated that musical stimuli containing irregular chord functions were generally perceived as more emotional [9], and less expected [10], than regular functions. Using functional magnetic resonance imaging (fMRI), two previous studies on the processing of regular versus irregular chord functions reported activations of orbito-frontal [3], as well as orbito-frontolateral cortex [4], taken to reflect emotive processing of the unexpected chords.

On the basis of Meyer's theory and the empirical findings mentioned above, we collected behavioral data on the valence percept of regular and irregular chord sequence endings. We hypothesized that valence ratings would differ between expected and unexpected chord sequence endings in both groups (no directed hypotheses were made about differences in valence judgements between groups). In addition, we reanalyzed a set of fMRI data investigating music-syntactic processing with the same chord sequences as those used in the behavioral study. In the reanalysis of this fMRI dataset, we tested a specific regional hypothesis, namely that unexpected (harmonically irregular) compared with expected chord sequences elicit differential activity changes in the amygdala, a key structure for emotional processing with regard to the generation, initiation, and termination of emotions [11]. In this study, we tested the specific regional hypothesis that amygdala activity can be modulated by the perception of unexpected chord functions.

Methods

Behavioral study

Participants

Data were obtained from two groups of participants: (i) nonmusicians (n=12; five females; age range 20–31 years; M=25.2 years), none of whom had any formal musical training (except normal school education), and none of whom played a musical instrument; and (ii) musicians (n=12; six females; age range 21–32 years, M=25.3 years) who had learned an instrument for 9–19 years (M=16 years). Participants were right handed (all had a laterality quotient >90 according to the Edinburgh Handedness Inventory), and reported having normal hearing. None of the participants took part in the fMRI experiment. Written informed consent was obtained and the study was approved by the Local Ethics Committee of the University of Leipzig and conducted in accordance with the Declaration of Helsinki.

Stimuli

Stimuli were identical to an earlier experiment [3]. A pool of stimuli consisted of 72 different chord sequences, each sequence consisting of five chords (Fig. 1a). Two types of sequences were used: sequences consisting of regular chord functions only (always ending on a tonic chord), and sequences ending on an irregular Neapolitan sixth chord (which is a less regular ending than the tonic chord in any kind of major–minor tonal music). Chord sequences were presented with different melodic outlines. Each sequence had a duration of 4000 ms: presentation time of chords 1–4 was 666.7 ms per chord and presentation time of chord 5 was 1333.2 ms (examples can be downloaded from *www.stefan-koelsch.de/fMRI_Neapolitan_sequences*). Chords were presented using a ROLAND JV 1010 synthesizer (Roland Corporation, Hamamatsu, Japan) with a piano timbre (General MIDI #1). The musical stimulus was played with approximately 75 dB SPL using MRI-compatible headphones with piezo-electric transmission.

Each participant performed two directly succeeding runs, each run consisting of 96 sequences. The 96 sequences were divided into 32 mini-blocks (each mini-block comprising three sequences). There were two types of mini-blocks: (i) mini-blocks consisting of regular sequences and (ii) mini-blocks in which sequences ended on irregular (Neapolitan) chords. In each run, 22 mini-blocks of type (i) and 10 mini-blocks of type (ii) were presented (thus, in each run 66 sequences ended on a tonic and 30 sequences on a Neapolitan chord). Mini-blocks were randomly intermixed in a way that up to three mini-blocks of type (i) were presented before the presentation of a mini-block of type (ii) (see Fig. 1b). In each mini-block with Neapolitans, the tonal key was once shifted one semitone upward with the onset of the second sequence (corresponding to the tonal key of the Neapolitan chord in the preceding chord sequence) to prevent the musical stimulus from becoming monotonous. This key shift introduced an additional harmonic irregularity (the change of a tonal key), no key shifts were used in the regular type (i) mini-blocks.

Procedure

Participants listened to the musical stimulus through headphones under the instruction to rate the emotional valence (pleasantness/unpleasantness) of the final chord of each chord sequence on a scale from 1 (very unpleasant) to 10 (very pleasant) using a PC keyboard. All participants were instructed not to pay attention to how 'well' or 'badly' the chords fitted into the chord sequence, but only to assess their valence percept. Before the experiment, samples of the two sequence types were presented to the participants until they said that they recognized the difference between the two sequences (usually 2–4 sequences).

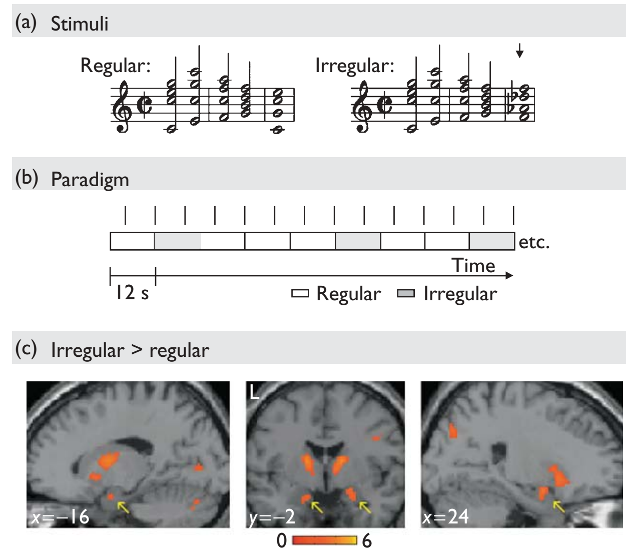

Fig. 1 Example of a chord sequence ending on a music-syntactically regular tonic chord (left), and of a sequence ending on an irregular Neapolitan sixth chord (right, the Neapolitan chord is indicated by the arrow). Note that this chord played in isolation is a normal, consonant chord. In the experiment, 72 different chord sequences were presented in all 12 major keys. (b) Experimental design. The rectangles indicate mini-blocks, each comprising three chord sequences (resulting in a length of 12 s per mini-block). White rectangles indicate mini-blocks with sequences ending on (regular) tonic chords, gray rectangles indicate mini-blocks with sequences ending on (irregular) Neapolitan chords. Vertical lines indicate functional MRI scans (repetition time=6 s, clustered volume acquisition). (c) Statistical parametric maps for the contrast irregular versus regular chords (irregular > regular chords, $P<0.05$, uncorrected), data were pooled for both groups of participants (n=20). In both hemispheres, irregular chords elicited activity changes within the amygdala (yellow arrows).

Functional MRI experiment

Participants

Data were obtained in an earlier study [3] from two groups of participants (each group consisted of 10 individuals: five males and five females), none of whom participated in the behavioral experiment. One group consisted of nonmusicians (age range 20–36 years, M=25.6 years) who did not have any formal musical training (except normal school education). None of the nonmusicians played a musical instrument. The other group consisted of musically trained individuals (age range 21–34 years, M=26.8 years) who had learned and studied a musical instrument for 4–18 years (M=9.4 years) at the time they participated in this study. The participants were right handed (laterality quotient of all nonmusicians was >90, of all musicians >75 according to the Edinburgh Handedness Inventory), and reported having normal hearing. Written informed consent was obtained and the study was approved by the Internal Review Board of the

Beth Israel Deaconess Medical Centre (Boston, Massachussetts, USA) and conducted in accordance with the Declaration of Helsinki.

Stimuli and procedure

The stimuli and procedure were identical to those described for the behavioral experiment, except that the participants were not asked to rate the emotional valence of any of the stimuli. Instead, they were asked to press one of two buttons on the last chord of each sequence: one button for the regular sequence ending (tonic chord) using the index finger, and another button for the irregular ending (Neapolitan chord) using the middle finger of the same hand.

Data acquisition and analysis

Functional MRI was performed on a 'General Electric' 3-T MR scanner. Twenty-four axial fMRI images were acquired with an effective repetition time of 6 s using a clustered volume acquisition lasting 1.75 s (to minimize interferences with the magnetic resonance scanner noise as well as auditory masking effects). A high-resolution T1-weighted scan ($1 \times 1 \times 1.5$ mm voxel size) was acquired for each participant for anatomical coregistration before the functional imaging experiment. fMRI data were analyzed using the SPM5 software package (Institute of Neurology, London, UK). After realignment, coregistration, normalization, and smoothing (8 mm full-width at half-maximum), condition and participant effects were estimated using a general linear model. The effects of global differences in scan intensity were removed by scaling each scan in proportion to its global intensity. Data were convolved with the hemodynamic response function, and low-frequency drifts were removed using a temporal high-pass filter with a cut-off of 108 s. In addition, a low-pass filter (hrf) was applied. A block design analysis was used (fixed effects) to contrast the experimental condition (irregular Neapolitan chord at the end of the chord sequence) with the control condition (regular tonic chord at the end of the chord sequence).

In the data analysis of our earlier study [3], we identified brain activations using statistical parametric maps (SPMs) of the entire brain with a statistical threshold of P value less than 0.05 (corrected for false discovery rates). In the present analysis, we tested the specific regional hypothesis that amygdala activity can be modulated by the perception of unexpected chord functions in two steps. First, we reinvestigated the SPMs of the contrast irregular greater than regular chords in the region of the amygdala using the SPMs with a statistical threshold of P value less than 0.05 (uncorrected). In a second step, we tested whether the observed amygdala activations were significant by using a small volume correction (SVC) with a sphere ('region of interest') of 3 mm radius (centered at the local maximum within the left and right amygdala, respectively) and a statistical threshold of P value less than 0.05 corrected for family-wise errors (FWE).

Results

Behavioral data

Means of grand-averaged valence ratings for the regular chord sequence endings (on a scale from 1 to 10) were 7.0 (SD=0.77) for nonmusicians and 7.4 (SD=1.4) for musicians. Valence ratings for the irregular endings were 2.8 (SD=0.69) for nonmusicians and 3.6 (SD=1.34) for musicians. Thus, regular endings were rated as rather pleasant, whereas irregular endings were rated as rather unpleasant. An analysis of variance with the factors chord (regular, irregular) and group indicated a main effect of chord [$F(1.22)=136.9$, $P<0.0001$, reflecting that regular chords were perceived as more pleasant than irregular chords], a marginal effect of group [$F(1.22)=136.9$, $P=0.059$, reflecting that musicians tended to rate both regular and irregular endings as more pleasant than nonmusicians], but no two-way interaction ($P=0.47$), indicating that the difference in valence ratings between regular and irregular chords did not differ between groups. As no two-way interaction was indicated, we investigated the fMRI contrast between irregular and regular chords pooled for both groups of participants.

Functional MRI data

Figure 1c shows the SPMs of the contrast irregular greater than regular chords (statistical threshold: $P<0.05$, uncorrected, see Methods). In the amygdala (bilaterally), signal changes were observed in response to irregular chords, and an SVC (using a sphere with 3 mm radius, centered at the local maximum within the left and right amygdala, respectively) indicated that the activation of the left (Talairach coordinate: -16 -3 -18), as well as that of the right amygdala (Talairach coordinate: 24 -1 -12) was significant on the voxel level (left: $P<0.05$; right: $P<0.002$, both values FWE corrected). Figure 1c also shows activation of the left and right dorsal striatum (caudate nucleus), but no directed hypotheses had been made regarding this cerebral structure. However, to generate hypotheses for future studies, we report here that these activations were located at Talairach coordinates -14 2 10 (left) and 16 -4 12 (right), and that both activations were statistically significant on the voxel level (both $P<0.001$, FWE corrected) as indicated by an SVC (using a sphere with 3 mm radius centered at the local maxima of activations). Note that no activations were indicated in the ventricles, or outside the brain (as can be seen in Fig. 1c), rendering it unlikely that the activations reported here were spurious.

Discussion

The irregular chord functions were judged as clearly more unpleasant than the regular chords, in both groups of participants. This corroborates previous findings showing that Bach chorales containing music-syntactically irregular chords are perceived as more emotional, that irregular chord functions are perceived as having greater musical tension, and that irregular chord functions occurring in short excerpts of piano sonatas are perceived as less pleasant than regular functions [9,10]. Importantly, our data show that music-syntactically irregular chord functions not only engage cognitive processes related to the analysis of the musical structure, as shown in earlier studies [1–5], but also emotional processes related to the unexpectedness (and the lower emotional valence of unexpected chord functions in chord sequence paradigms) of irregular chord functions. This finding has important implications for the interpretation of fMRI data obtained in experiments investigating (music) syntactic processing, as will be described in more detail below.

The fMRI data show that amygdala activity can be modulated by the perception of irregular (compared with regular) chords. This extends our knowledge about the involvement of the amygdala in music processing: Earlier studies have shown activity changes in the amygdala in response to highly unpleasant music (permanently strongly dissonant) contrasted to pleasant music [12], to frightening music paired with pictures [13], to frightening as well as happy music paired with film clips [14], and in response to extremely pleasurable experiences such as 'chills' during music listening [15] (in the latter study, decreasing chills intensity correlated with increasing regional cerebral blood flow in the amygdala). Our results show that simply a music-syntactic irregularity can elicit an amygdala response, providing further evidence of the impact of music on brain structures that are crucially involved in human emotion. This is relevant because affective disorders such as depression or pathologic anxiety have been associated (among other causes) with amygdala dysfunction [16,17], and the findings that amygdala activity can be modulated by music perception provide potential music–therapeutic approaches for the treatment of such affective disorders with a scientific basis [18].

The combined findings of the fMRI and the behavioral experiment also corroborate Meyer's theory on music and emotion [8] (see Introduction) in that they show that irregular chord functions represent a route to the elicitation of emotional responses in the listener. Notably, a Neapolitan chord itself is a consonant, 'normal' chord: it is principally the music-syntactic relation (i.e. the harmonic relation to the preceding chords of the sequence) in which this chord sounds irregular and unexpected (at least for listeners familiar with major–minor tonal, i.e. 'Western' music). These results thus yield that neuroimaging studies on musical syntax processing should take into account the fact that irregular chords may also elicit emotional responses, and that the activation pattern might be explained in part by the perceived valence of chord sequences. Such caution may also be appropriate with regard to experiments investigating language-syntactic processing, or even the processing of complex sequences in general.

Activation of the amygdala in response to unexpected events has also been reported in the non-musical domain, for example, following the unexpected infusion of cocaine [19], or in affective priming paradigms with words [20]. The notion that the amygdala plays a role in the processing of unexpected musical events also fits with earlier observations of blood oxygen level-dependent signal changes in the orbito-frontal cortex [3,4] in response to the irregular chord functions: The amygdala is anatomically and functionally connected with the orbito-frontal cortex [21], which has been reported to be activated by 'breaches of expectations' [22].

Pronounced activity changes in response to harmonically irregular chords were also observed in the dorsal striatum. We did not have directed hypotheses about activations in the dorsal striatum, but future studies aiming to test this further could take into account that the dorsal striatum – besides its involvement in procedural and habit learning – also plays a role in motor memory related to emotional experiences, particularly in interaction with the amygdala [23] (for relations between emotion and motor activity during music listening see [24]). On account of its role in procedural processing, the caudate might also be involved in the processing of syntactically unexpected events during both music [2] and language processing [25], or in a more general processing of unexpectedness in complex sequences [1] (in the latter study, caudate activation was elicited by deviant instrument clusters embedded in chord sequences).

Conclusion

The results of this study show that music-syntactically irregular chord functions differ in their emotional valence from regular chord functions, and that these different chord types elicit differential responses in the amygdala. This shows that, with regard to music, activity changes in the amygdala cannot only be elicited by music that is perceived as intensely pleasurable, or as highly unpleasant, but also even by single chord functions embedded in chord sequences that are perceived as unexpected and less pleasant than expected sequences.

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