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The Role of Harmonic Expectancy Violations in Musical Emotions: Evidence from Subjective, Physiological, and Neural Responses

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Abstract

■ The purpose of the present study was to investigate the effect of harmonic expectancy violations on emotions. Subjective response measures for tension and emotionality, as well as electrodermal activity (EDA) and heart rate (HR), were recorded from 24 subjects (12 musicians and 12 nonmusicians) to observe the effect of expectancy violations on subjective and physiological measures of emotions. In addition, an electroencephalogram was recorded to observe the neural correlates for detecting these violations. Stimuli consisted of three matched versions of six Bach chorales, which differed only in terms of one chord (harmonically either expected, unexpected or very unexpected). Musicians' and nonmusicians' responses were also compared. Tension, overall subjective emotionality, and EDA increased with an increase in harmonic unexpectedness. Analysis of the event-related potentials revealed an early negativity (EN) for both the unexpected and the very unexpected harmonies, taken to reflect the detection of the unexpected event. The EN in response to very unexpected chords was significantly larger in amplitude than the EN in response to merely unexpected harmonic events. The ENs did not differ in amplitude between the two groups but peaked earlier for musicians than for nonmusicians. Both groups also showed a P3 component in response to the very unexpected harmonies, which was considerably larger for musicians and may reflect the processing of stylistic violations of Western classical music. ■

INTRODUCTION

It is widely accepted that cognitive processes are involved in the generation of emotional states (Frijda, 1993, Smith & Lazarus, 1993). Among these, expectation appears to play a particularly important role, leading to surprise or disappointment, satisfaction or contentment (Dennett, 1991).

Meyer (1956) proposed that many musical emotions are caused by fulfilled or suspended musical expectations. He claimed that listeners have implicit expectations of what will happen in the music and, depending on whether these expectations are fulfilled or not, listeners will experience relaxation or tension and suspense. Such expectations can arise through implicit knowledge of musical rules and regularities, acquired through repeated exposure to a particular style, such as Western tonal music (Tillmann, Bharucha, & Bigand, 2000).

The present study provides a direct test of the role of music-specific expectations in the generation of emotional response in the listener. Musical expectations have been studied for melody, rhythm (see Boltz, 1993; Narmour, 1990; Jones, Boltz, & Kidd, 1982), and harmony (see previous studies by Schmuckler, 1989; Bharucha & Stoeckig, 1986). However, the present study focuses on harmony only. This is because harmonic violations can be easily quantified in music-theoretically justifiable terms by using the Circle of Fifths, as well as adding to a considerable body of event-related potential (ERP) literature on chord processing (Koelsch, 2005; Koelsch & Siebel, 2005).

To investigate the cognitive processes underlying harmonic expectation, Bharucha and Stoeckig (1986) employed a priming paradigm, where stimuli consisted of two chords, a prime and a target. It was hypothesized that if harmonic expectations were present, judgments about the target chord (major/minor; in-tune/out-of-tune) should be facilitated by certain prime chords and slowed down by others. The results suggested that harmonic expectations are based on relations of harmonic distance (as described by the Circle of Fifths; see Figure 1). The closer the harmonic relationship between the prime and the target chord, the faster the target-judgment was made. Harmonic expectation does not require the conscious knowledge of the listener but can arise through implicit processing of harmonic relations (Bigand, Tillmann, Poulin, d'Adamo, & Madurell, 2001), which mirror the principles of harmonic relatedness

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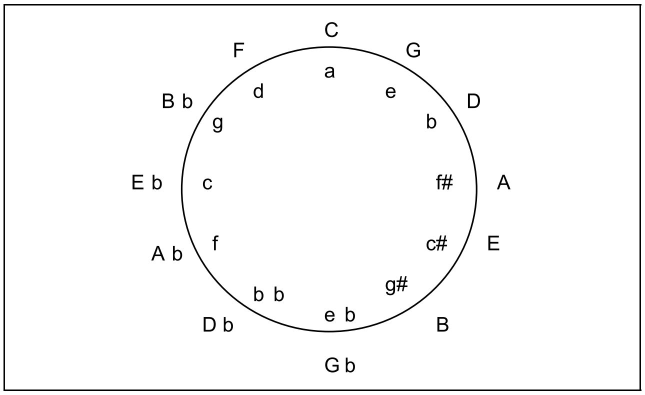

Figure 1. Circle of Fifths: The outer upper-case symbols represent major keys and the adjacent inner lower-case symbols represent the relative minor keys (i.e., C major–a minor). The closer the keys, the closer their harmonic relationships, which are indicated by the number of scale-notes in common: with direct neighbors, this is six notes, with neighbors once removed, this is five notes, and so forth.

underlying Western music (Tillmann et al., 2001; Koelsch, Gunter, Friederici & Schroeger, 2000; see Figure 1).

It has been shown that the harmonic distance between two keys is related to the tension contained in the music as judged by the listener, in studies using chord sequences of varying lengths (Bigand, Madurell, Tillmann, & Pineau, 1999; Bigand, Parncutt, & Lerdahl, 1996) and in studies using real music (Toiviainen & Krumhansl, 2003; Krumhansl, 1996; 2002). Chords far away from the tonal root will tend to produce perceptions of tension because more expected harmonic events are suspended (Lerdahl & Jackendoff, 1983). We will argue that perceived tension in the music can be related to felt emotion. However, we consider tension to be a distinct and separable psychological concept.

Bigand et al. (1996) presented listeners with three-chord sequences where an initial and final root chord was separated by another chord with varying harmonic distance from the root chord. Participants were asked to rate the amount of tension produced by the middle chord. Listeners found the middle chord as increasingly tense the further it moved in harmonic distance from the root chords by which it was framed. In another experiment, Krumhansl (1996) obtained several perceptual ratings, including tension, from listeners to a Mozart piano sonata, measured continuously as the music was playing. Analysis revealed that features such as the interruption of a harmonic progression, or a key change, were responsible for increases in perceived tension. In sum, these studies suggest that the less expected a harmonic event is to the listener, the more musical tension will be perceived. This is important for the present study because musical tension seems to represent a link between expectation and emotion. Several studies have shown that there is a high correlation between the amount of tension perceived in the music and how emotional the listener feels in response to the music. For instance, in a study on the expressive properties of dance and music, Krumhansl and Schenck (1997) asked participants to continuously rate both the amount of tension and the expressed emotion of the music by means of an adjustable foot-pedal, indicating the strength of their responses. It was found that the two ratings correlated very highly on both a moment to moment and a whole-piece level. In another study by Krumhansl (1997), psychophysiological measures were taken during exposure to musical extracts of different emotional character, and participants were asked to rate the tension and emotional mood perceived in the music. The dominant mood of each piece, as rated by the listener, was found to correlate highly with the rated tension. These studies are suggestive of a link between the perception of tension and emotion in music on both a local as well as a global level.

Another relevant study was carried out by Sloboda (1991) in which retrospective subjective accounts of physiological manifestations of emotional responses to music listening were obtained. Participants were asked to identify specific passages in compositions that reliably elicited these responses. An analysis of the musical structure of the cited passages was able to link specific physiological responses to specific musical structures. It was revealed, among other things, that heart racing tended to be associated with a prominent event occurring earlier than expected and that shivers and pilo-erection tended to be associated with new or unprepared harmonies. The study adds further evidence that the unexpected in music is capable of eliciting emotions in the listener. It also adds support to the notion that there are several pathways to emotion in music and that unexpected harmonic events are only one among many (Scherer & Zentner, 2001).

In summary, it appears that the further a harmonic event is from its tonal center, the less expected it is and the tenser it will appear to the listener. This in turn will increase the amount of emotion in the listener. Tension is thus an important connecting concept, establishing what it is about the unexpected that makes it emotional.

What is still lacking in the literature is a demonstration of a direct link between an unexpected musical event and an emotional response. Sloboda's (1991) self-report study suggests that this is possible, but it has not yet been studied in a controlled experimental setting with an objectively measurable emotional response.

The present study included two physiological measures as indicators of emotional processing, namely, the inter-heartbeat interval (IBI) and electrodermal activity (EDA). These two measures have been consistently associated with the valence and the arousal dimension of the emotional experience, respectively (Bradley & Lang 2001; Bradley, Lang, & Cuthbert, 1993; Lang, Greenwald, Bradley, & Hamm, 1993). Arousal refers to the degree of emotional intensity and valence to the perceived un-/

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pleasantness of the stimulus. Using these two measures thus provides data on the two central dimensions of emotional response. In relation to emotional processing in music, only some studies have looked at physiological measures systematically. Krumhansl (1997) used a variety of physiological measures to investigate emotional processing including, among others, IBI and EDA. Sad excerpts seemed to most strongly affect the cardiac and electrodermal systems, whereas fearful excerpts mainly influenced cardiovascular measures and happy excerpts respiratory ones. This suggests that specific emotions experienced in response to music involve particular physiological characteristics.

Focusing on one physiological variable, Khalfa, Peretz, Blondin, and Manon (2002) studied emotional arousal levels by measuring EDA in response to pieces of music selected to represent and elicit one of four emotions: happiness, sadness, fear, and peacefulness. It was found that the two intuitively more arousing of the four emotions, fear and happiness, produced greater EDA than sadness and peacefulness, and it was concluded that EDA is a better indication of whether a musical stimulus is arousing as opposed to its emotional valence (i.e., sad or happy).

A considerable body of literature has explored the neural processing of expectancy violations. Koelsch et al. (2000) investigated how music processing in the brain is influenced by a preceding musical context and by the degree and the probability of a harmonic expectancy violation. The experimental paradigm entailed playing five chords, which would usually consist of an expected in-key harmonic progression starting and ending on the tonic, with the dominant seventh as the penultimate chord, followed by the final tonic (a prominent marker for the termination of a harmonic sequence). To investigate the neural processes underlying the violation of musical expectancy, out-of-key chords were presented infrequently at either third or fifth position of the chord sequence. In other words, harmonically unrelated chords were played, which in this case were so-called Neapolitan Sixths. Neapolitan chords are variations of the minor subdominant chord of the home key, with a diminished sixth instead of a fifth (in C-major: f-a flat–d flat). Because the Neapolitan Sixth is based on the minor subdominant, the chord features two out-of-key notes in major keys (in C major: a flat and d flat) and one out-of-key note in minor keys (in C-minor: d flat), and could therefore be described as highly unexpected. However, Neapolitan chords are not in themselves dissonant, but consonant chords.

Event-related brain potentials elicited by the unexpected chords revealed two effects: an early right anterior negativity (ERAN) peaking around 180 msec, taken to reflect the violation of harmonic expectancy, and a late bilateral frontal negativity peaking at 500–550 msec (hence, referred to as N5), taken to reflect the higher processing effort needed to integrate unexpected harmonies into the ongoing musical context.

The ERAN was found to be larger when the Neapolitan was at fifth position than at third position in the chord sequence (Koelsch et al., 2000). The explanation for this is likely to be that by the fifth position the listener had built up stronger musical expectations as a result of processing more prior chords, and so the expectancy violation was greater.

These findings have been taken as evidence that the brain is sensitive to harmonic violations, given a sufficient sense of harmonic context, and have been replicated in several subsequent studies (see Koelsch, 2005; Koelsch & Siebel, 2005). Because the ERAN effect was found in nonmusicians, this strongly suggests that all listeners familiar with Western tonal music have an implicit sense of tonality. However, Koelsch, Schmidt, and Kansok (2002) discovered that the neural sensitivity for harmonic expectancy violations was greater in musicians than in nonmusicians, suggesting that musical training influences the processing of harmonic relationships. Additionally, Koelsch and Mulder (2002) found that nonmusicians were able to detect inappropriate harmonies in piano music by classical composers, as indicated by an ERAN-like effect, a finding relevant to the present study, as the stimuli were examples of real music.

The stimuli for these EEG studies have also been used in an fMRI study (Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005) in which strong activations of the frontal operculum (BA 44, which in the left hemisphere is also referred to as part of Broca's area) were observed in response to the harmonic expectancy violations. This structure has been implicated in the processing of structural irregularities, in both music and language (Koelsch, 2005; Friederici, 2002). The activation of the frontal operculum was found to be stronger for musicians than for nonmusicians, supporting the previous EEG findings by Koelsch, Schmidt, and Kansok (2002). Interestingly, additional activations for both subject groups were observed in the orbital frontolateral cortex (OFLC), a paralimbic structure previously related to the evaluation of the emotional valence of a sensory stimulus, and the attribution of emotional valence to sensory information (Mega, Cummings, Salloway, & Malloy, 1997). The activation of the OFLC in response to harmonic expectancy violations suggests that activity in this brain structure might be due to emotional processing in response to these violations.

These EEG and fMRI studies used chords which were harmonically unexpected in a given context and elicited neural activity which has been argued to reflect music-syntactic processing, due to their close association with processes reflected in language-syntactic processing (Friederici, 2002). However, it is still unclear to what extent these unexpected harmonies also activate emotional processes.

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The theory outlined above and the observed activation of the OFLC increase the plausibility of such an idea. It was the purpose of the present investigation to explicitly test the hypothesis whether harmonic expectancy violations are also emotionally significant. Several dependent measures were employed to allow a more integrated analysis.

It was hypothesized that with increasing harmonic unexpectedness: (a) subjective emotional intensity immediately following the violation will be heightened, (b) the tension perceived in the music will be heightened, (c) the overall rated emotional intensity of the stimulus will be heightened, (d) an increase in physiological indicators of emotion will occur, (e) neural mechanisms will be elicited to process the increasing harmonic unexpectedness, specifically an ERAN and an N5, and (f) that musicians will show stronger reactions in all measures than nonmusicians because they should have internalized the rules of Western music more completely than nonmusicians and should therefore be more sensitive to their violations (Koelsch et al., 2005; Koelsch et al., 2002; Sloboda, 1985, 1992).

METHODS

Subjects

Twelve musicians (age range 19–29, mean age 25.15 years; 6 men) and 12 nonmusicians (age range 20–27, mean age 24.7 years; 6 men) participated in the study. On average, musicians had 13.8 years of musical training (range: 8.5–18.5), consisting of instrumental tuition and aural training received at a music conservatory. Nonmusicians did not have any musical training beyond that routinely provided in classroom music at school. All subjects were right-handed and reported to have normal hearing.

Stimuli

Stimuli consisted of excerpts from six different chorales by the composer J. S. Bach (Riemenschneider, 1941). These were either presented in their original form or minimally manipulated in two ways to produce either a more or a less harmonically expected version than the original (see Table 1). The original section of each chosen chorale was selected specifically for its unexpected harmonic structure at a particular point, generally a cadence. These points (which we will call "targets") were selected by musical intuition and then confirmed by calculating the distance of the chosen harmonic point from the home key. This distance was measured using the circle of fifths (see Figure 1) and working out the number of key-steps from both the home key and the key of the immediate context to the relevant harmonic point.

For each chorale, two alternative harmonizations of the target were composed, one which was more harmonically expected than the original and another which was less harmonically expected than the original. The more expected versions were always a return to the tonic (for five of the chorales, this was a return to the tonic of the piece; for one of the chorales, this was a return to the tonic of that particular section). In two cases, there was also a change in the melody prior to the expected harmonic event in order to accommodate the harmonic change. The very unexpected version was always a Neapolitan Sixth in relation to the home key (see the Introduction for a more detailed explanation of its harmonic construction and relationship to a given home key; see also Figure 2 for an example of a stimulus and its manipulations). For all very unexpected events, the melody had to be altered to fit the harmonic change.

The unexpected musical events, as composed by Bach, did not always possess the same degree of unexpectedness. The unexpected event was either the relative minor

Table 1. Chorales Used as Stimuli

Chorale (as indicated by Riemenschneider, 1941)	*Length of Entire Chorale (length of excerpt)*	*Placement of Targets within the Segment and Manipulation*
No. 7 (BWV 17.7): Nun lob', mein' Seel', den Herren.	46 bars (*bars 24–31*)	Bar 27—move to the subdominant
No 21 (BWV 153.5): Herzlich tut mich verlangen	17 bars (*bars 1–5*)	Bar 4—heightened chromaticism
No 52 (BWV 429): Wenn mein Stündlein vorhanden ist	16 bars (*bars 3–7*)	Bar 7—move to the subdominant
No 60 (BWV 133.6): O Stilles Gotteslamm	17 bars (*bars 11–17*)	Bar 15—move to the relative minor of the home key
No 84 (BWV 197.5): Nun bitten wir den heiligen Geist	15 bars long (*bars 8–15*)	Bar 13—move to the relative minor of the section key
No 276 (BWV 375): Kommt her, ihr lieben Schwesterlein	11 bars (*bars 5–11*)	Bar 9—heightened chromaticism

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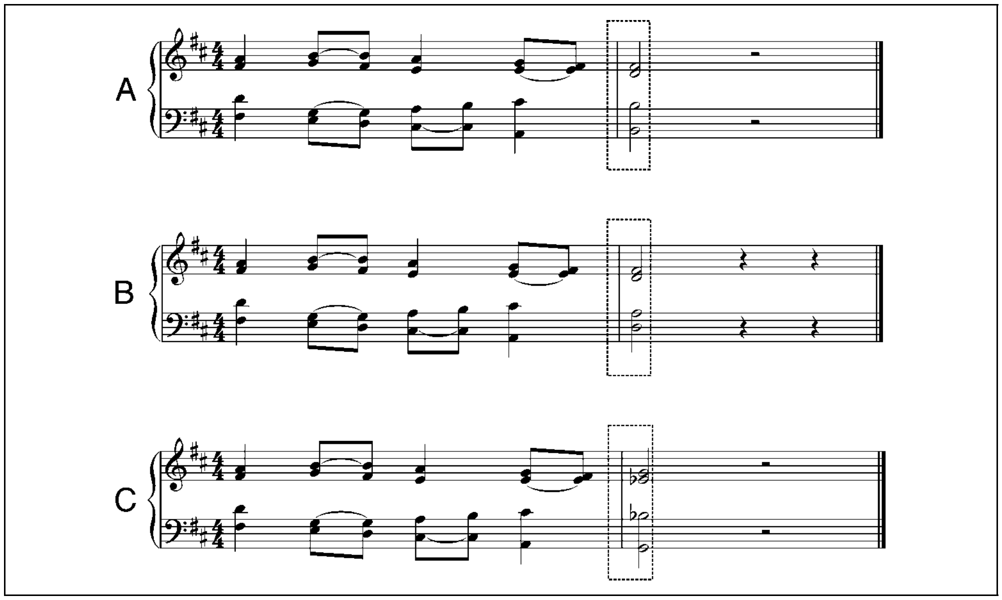

Figure 2. One example of a cadence within the stimulus set and its manipulations: Version A is an excerpt of the original composition by Bach, with a harmonically unexpected event (indicated by the dashed square); Versions B and C are identical to the original, apart from the harmonic events enclosed within boxes, which were rendered to be either harmonically more expected than the original (Version B) or less expected than the original (Version C).

(twice), more chromatic than the expected event (twice), or the subdominant chord as opposed to the tonic (twice) (see Table 1 for more detail). The target was always at least seven chords away from the end of the chorale.

In summary, there were three types of each stimulus: harmonically expected, unexpected (Bach's original), and very unexpected. With six chorales, this produced 18 stimuli in total.

Stimuli were taken from previously recorded MIDI files and altered in CuBase SX. The three versions of each chorale were identical apart from the harmonic event which was changed for each condition. The music was played without expressive features, and tempo and loudness were kept constant throughout.

Two versions of each stimulus were used: a full version (45–90 sec) for the continuous response measure, to allow for a cognitive response to the music to develop over a slightly longer time span; and a shortened version (9–20 sec) for the physiological data (EEG and EDA). To reduce the overall time of the experiment, the phrase containing the target was extracted from each chorale. Bach typically used *fermata* (musical resting points) to mark the end point of each phrase. These were used to identify the beginning and end of the shorter stimuli, thus retaining the most musically coherent stimuli possible.

The harmonic events of interest, both original and altered, had a total duration of between 650 and 1200 msec.

The stimuli were generated in Wave-Format with a piano sound using CuBase SX (Steinberg/Wizoo; Germany) for presentation during the experiment.

Procedure

The experiment consisted of two parts: a first behavioral part, which obtained continuous subjective ratings on the scales of tension and emotionality to the music as well as obtaining a final rating of overall emotionality at the end of each piece; and a second part, which recorded physiological measures (IBI, EDA) as well as an EEG.

The first part was divided further to allow recording of both tension and emotion ratings. Continuous emotion ratings were asked for the first three chorales, and tension ratings for the second three, the order of which was changed after every three subjects. To avoid any participant hearing different harmonizations of the same chorale, stimuli were rotated among participants following a Latin square design.

Participants indicated the extent of their emotional response or the amount of perceived tension using a keyboard, which controlled a moveable red slider displayed on the screen. The slider could be positioned at any intermediate point between two end points, which were marked as 0 and 100 for minimal and maximal amount of tension or emotion, respectively.

Depending on what participants were rating, the additional text was displayed on the screen: "Please indicate continuously how strong your emotional reaction is to the music that you hear!" or "Please indicate continuously how you feel the tension in the music that you hear is changing!". Responses were recorded every 100 msec.

At the end of each chorale, another rating from 1 to 10 was given of the overall emotionality in response to the music.

Participants were given as many practice trials with a practice chorale as they needed to acquaint themselves with the response interface.

After the practice, the behavioral part of the experiment began. After completing the ratings, the experiment was repeated. This repeat was taken into the statistical analysis, with the factor "block" thereby providing a measure of response reliability.

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The second part of the experiment constituted the joint measurement of IBI, EDA, and EEG. The order of chorales was pseudorandomized. A total of 108 stimuli were presented. Due to the limited number of chorales selected for the experiment, each version of each chorale was presented six times, adding up to 36 trials per condition. Repetition of individual stimuli was necessary to increase the signal-to-noise ratio.

For the physiological and neural data collection, participants were given another task to ensure that they were paying attention to the music. Continuous responses, as in the first part of the experiment, would have been undesirable due to muscular artifacts, which can obscure emotion-related EDA. The task was kept simple to reduce any arousal related to task complexity. Therefore, participants had to compare the length of each extract and indicate whether it was longer or shorter than the previously heard one. Participants were given a response-box to make their responses. There was no response feedback. To avoid a confound with event-related EDA, responses could only be made 2 sec after the music had ended.

After the response was made, there was another pause of 8 sec to allow EDA to return back to a baseline response.

Data Measurement and Analysis

For the measure of continuous responses, the literature reports a time-lag between musical event and response estimated to lie between 2 and 4 sec (Sloboda & Lehmann, 2001; Krumhansl, 1996). Having plotted individual responses onto a graph and observed no change in response after 3 sec poststimulus (point of original/manipulated harmony), the present study estimated a maximum time-lag of 3 sec. To reduce the amount of data from the continuous response measure, every 10 data points were averaged to one point, producing one response value for each second. Judgments were analyzed by analyses of variance (ANOVAs) as univariate tests of hypotheses for within-subject effects. For both continuous response scales (tension and emotionality), ANOVAs were conducted for the factors chord type (expected, unexpected, very unexpected), time (0–1 sec, 1–2 sec, 2–3 sec), block (first rating, second rating), and for the between-subject factor training (musician, nonmusician).

EDA, IBI, and EEG were recorded simultaneously using two 32/MREFA amplifiers (Twente Medical Systems, Enschede, Netherlands) and digitized with a sampling rate of 500 Hz. For the EDA measurement, two Ag–AgCl electrodes were placed on the medial phalanx of the middle and index fingers of the nondominant hand (always left) and attached with an adhesive tape. The sites were treated with alcohol 15 min prior to fixing the electrodes. After recording, the EDA was sampled down to 20 Hz and filtered with a low-pass filter of 8.5 Hz (599 points, fir). The EDA was visually inspected and checked for failures of the measuring device as well as movement-related artifacts, typically producing an unusually steep onset. Averages were computed with a 500-msec prestimulus baseline. Responses were considered if they occurred within a 1–3-sec latency window following stimulus onset, as described in the literature (Khalfa et al., 2002). ANOVAs were conducted for the factor chord type in a time window of 1–5 sec and for the between-subject factor training.

For the IBI measurement, two electrodes were placed on the upper biceps of the left and right arms. After recording, the data were filtered using a band-pass filter with a frequency range of 2–60 Hz (801 points, fir). Instantaneous heart rate (bpm) was calculated based on the length of R–R peak intervals. Averages were computed with a 1-sec prestimulus baseline as described in the literature (Bradley & Lang, 2000). ANOVAs were conducted over 2-sec time windows from 0 to 6 sec poststimulus for the factors chord type and training.

The EEG was recorded using Ag–AgCl electrodes from 32 locations of the 10–20 System referenced to the left mastoid (Pivik et al., 1993). The ground electrode was placed on the sternum. Additionally, a horizontal electrooculogram (EOGH) was recorded, placing electrodes between the outer right and outer left canthus, for a subsequent identification of eye-movement-related artifacts. The vertical electrooculogram (EOGV) was recorded placing an electrode on the nose and another at Fpz. The EEG data were filtered off-line using a band-pass filter with a frequency range of 0.25–25 Hz (3001 points, fir). To remove eye-movement-related artifacts from the EEG data, data were excluded if the standard deviation of the horizontal eye channel within a gliding time window of 200 msec exceeded 25 μV. To eliminate movement-related artifacts and drifting electrodes, data were excluded if the standard deviation within the time window of 800 msec exceeded 30 μV. On average, 12.2% of all trials were rejected from further data analysis. Averages were computed with a 200-msec prestimulus baseline.

Mean ERP values were computed for four separate regions of interest (ROIs): left anterior (F7, F3, FT7, FC3), right anterior (F8, F4, FC4, FT8), left posterior (C3, CP5, P7, P3), and right posterior (C4, CP6, P4, P8). ANOVAs were conducted with the factors chord type, training, hemisphere (left × right ROIs) and anterior/posterior (frontal × parietal ROIs). ERP amplitude peak times were also compared for the two groups with the factor peak time for which mean ERP latencies were computed of all electrodes.

RESULTS

Continuous Response Data

For the continuous response part of the experiment, the experiment was repeated to assess the rating reli-

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ability. Correlation coefficients between the first and the second ratings were calculated. Pearson's correlation coefficient, used to indicate the reliability of the continuous responses, indicated a highly significant positive correlation for both continuous emotionality and tension ratings, with $r = .571$, $p < .001$ and $r = .771$, $p < .001$, respectively. Additionally, emotional impact ratings given at the end of each of the two repetitions of the same piece correlated very highly with one another ($r = .908$, $p < .001$). These significant correlations indicate that participants judged tension and emotionality reliably.

As already mentioned, for the following statistical analysis, both ratings on each scale were included in the analysis with the factor block.

Continuous emotionality judgments, which were recorded on a 100-point linear scale representing the position of the slider on the screen, showed no increase with harmonic unexpectedness over the 3-sec poststimulus and no interaction between any of the factors.

Tension judgments, on the other hand, appeared to increase over time with unexpectedness of the harmonic events (see Figure 3). An ANOVA for tension judgments with the factors chord type, time, training, and block revealed an interaction of chord type and time [$F(2,162) = 3.111$, $p < .05$], such that the increase in tension was greatest for the most unexpected harmony. There were no further significant interactions between any of the other factors.

The emotional impact ratings given at the end of each piece (see Figure 4) also increased significantly with the increase of unexpectedness of harmonic events embedded in the music. An ANOVA with factors chord type, training, and block showed a highly significant effect for the factor chord type only [$F(2,141) = 17.591$, $p < .0001$]. Post hoc tests showed a significant difference between all three conditions (expected vs. unexpected: $p < .05$; expected vs. very unexpected: $p < .0001$; unexpected vs. very unexpected: $p < .001$).

Physiological Data

For the behavioral task performed while recording the physiological data (judging piece length), 79.9% of all keypresses were correct, indicating that participants paid sufficiently close attention to the music.

Inter-heartbeat Interval

There were no significant changes in the IBI for the three different types of harmonization in any of the three time windows (0–2 sec: $p > .5$; 2–4 sec: $p > .9$; 4–6 sec: $p > .4$).

Electrodermal Activity

The EDA in response to the three different types of harmonization were compared over the time course of 5 sec because any stimulus-related electrodermal activity was expected to occur in that time window (see Methods). As was hypothesized, the three EDA curves begin to diverge around 2 sec poststimulus, increasing most for the EDA response to very unexpected harmonies and little less for the EDA response to unexpected harmonies (see Figure 5).

An ANOVA with the factors chord type and training revealed a significant effect of chord type [$F(2,46) = 6.15$, $p < .01$] and no two-way interaction. Comparisons between each condition revealed significant differences between expected and unexpected chords [$F(1,23) = 7.77$, $p < .05$], and expected and very unexpected chords [$F(1,23) = 10.29$, $p < .01$], but none between unexpected and very unexpected chords ($p < .3$) (significance levels were Bonferroni-corrected).

Electroencephalogram

Early Negativities

As can be seen in Figures 6 and 7, the very unexpected chord (Neapolitan Sixth) elicited a distinct early negativity (EN) for both groups, peaking slightly earlier for

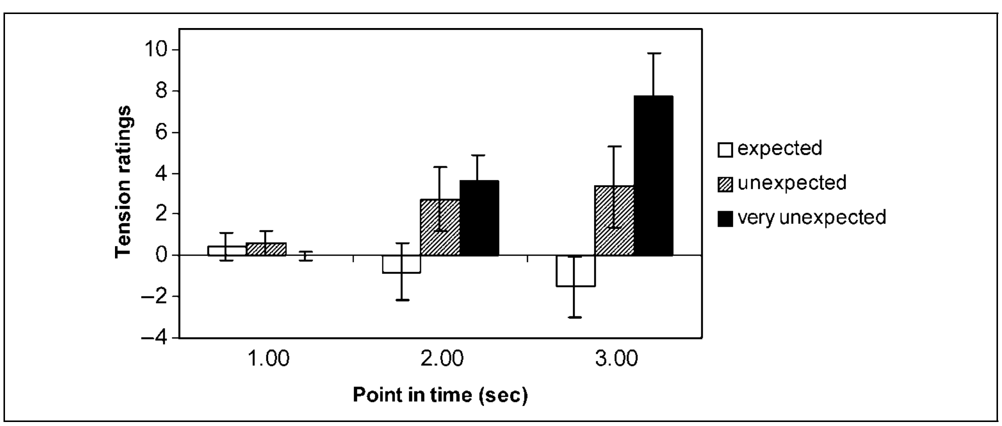

Figure 3. Mean and standard error of tension responses to chords of different expectedness over time. Presented values were derived by subtracting the value at time 0 from the successive judgments to obtain an absolute value of increase/decrease in response to the harmonies. Tension ratings significantly increased with harmonic unexpectedness.

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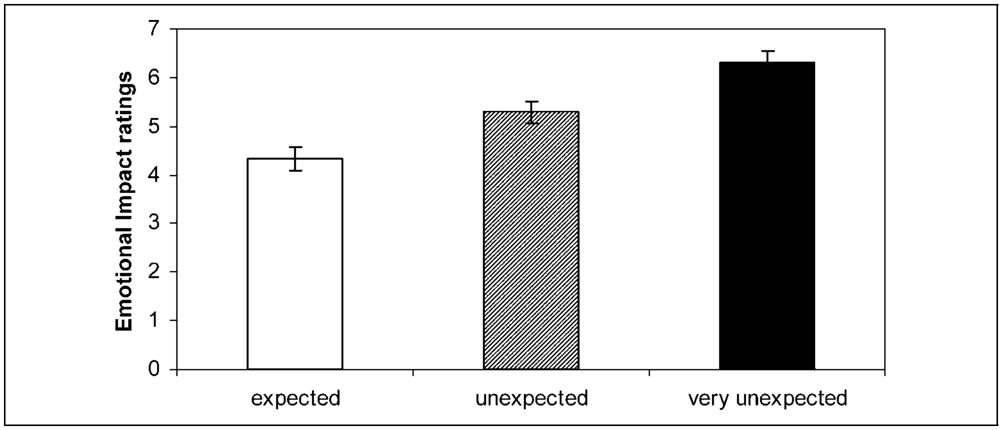

Figure 4. Mean and standard error of overall emotional impact ratings given at the end of the music. The overall emotionality clearly increased in response to increases in harmonic unexpectedness.

musicians (around 200 msec) than for nonmusicians (around 230 msec). This negativity was broadly distributed over the scalp and resembles the ERAN reported in previous studies (Koelsch & Friedrici, 2003; Koelsch, & Mulder, 2002; Koelsch, Schmidt, & Kansok, 2002; Koelsch, Gunter, Friederici, et al., 2000). As a result of this broad distribution, we will refer to this component more generally as an EN, although we assume it to be functionally the same as the ERAN.

Peak latencies of this ERP were compared between the two groups because it was 30 msec earlier for musicians than for nonmusicians. An independent-subjects *t* test for the factor peak time revealed a marginally significant difference between the two groups [$t(22) = -2.048$, $p = .053$].

ANOVAs for frontal ROIs with different time windows for each group (musicians: 180–230 msec; nonmusicians: 200–250 msec), with factors chord type, hemisphere, anterior/posterior, and training, revealed a significant effect of chord type [$F(1,22) = 11.43$, $p < .005$], but no interaction between any of the factors. Although this EN looks considerably larger for musicians than for nonmusicians, this was not confirmed statistically.

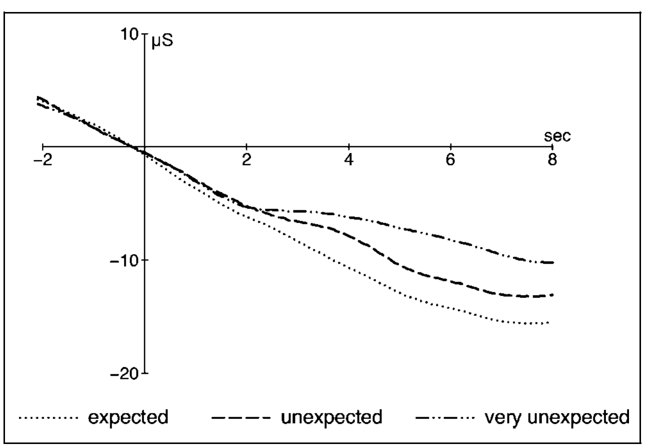

Figure 5. Averaged EDA of all participants in response to the three different types of harmonizations. The *y*-axis of µSiemens (µS) represents relative (not absolute) values (thus, any negative value on this scale does not exist in an absolute sense, but indicates a decline in EDA over time).

The EN was followed by a large positivity particularly for musicians, which will be reported in detail further below. Although it was hypothesized that an N5 would be elicited, the large positivity preceding the ERP reduces the size of this component and the N5 was thus nonsignificant.

The unexpected chord (composition in its original form) also elicited an EN for both groups, however, considerably earlier for musicians (around 210 msec) than for nonmusicians (around 310 msec) (see Figures 6 and 7) and with a slight left-anterior preponderance for the latter group. Because the ERP was elicited approximately 100 msec earlier for the musicians, this difference was explicitly tested. An independent-subjects *t* test for the factor peak time revealed a significant difference between the two groups [$t(22) = -3.585$, $p < .005$].

ANOVAs for frontal ROIs with different time windows for each group (musicians: 190–240 msec; nonmusicians: 290–340 msec), with factors chord type, hemisphere, anterior/posterior, and training, revealed an effect of chord type [$F(1,22) = 4.79$, $p < .05$], but no interactions between any of the factors.

The distributions of the ENs elicited by both very unexpected and unexpected chords (henceforth ENvx and ENux, respectively) appear to be strongest over fronto-central sites. It is assumed that these negativities are generated at the same or very similar sources and reflect the processing of harmonic expectancy violations. Because the Neapolitan Chord was less expected than the unexpected harmonies used in the original compositions, and because previous findings suggest the ERAN amplitude to be sensitive to the degree of harmonic violation (Koelsch et al., 2000), the amplitudes of the ENvx (time windows: 180–230 msec/200–250 msec) and of the ENux (time windows: 190–240 msec/290–340 msec) were compared. An ANOVA with the factors negativity and training revealed a marginally significant effect of negativity [$F(1,22) =$

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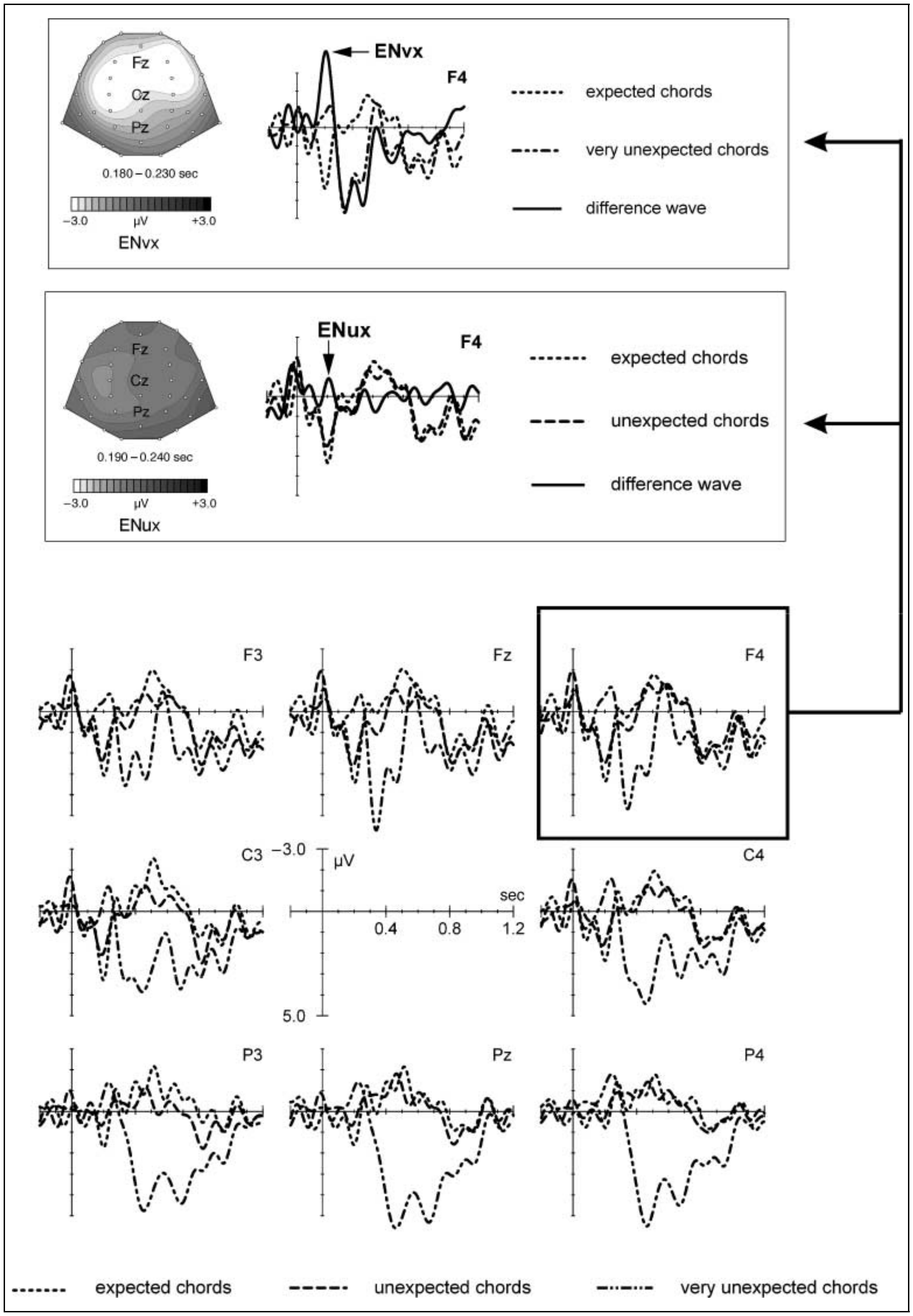

Figure 6. ERP responses to harmonic expectancy violations for musicians. ERPs to all three harmonic conditions are displayed at the bottom. Arrows from the F4 electrode point to displays of the difference waves between the expected and one of the unexpected conditions (top: very unexpected − expected = ENvx; bottom: unexpected − expected = ENux) and their distributions over the scalp (interpolated over the indicated time windows).

3.99, $p = .058$], indicating the ENvx to be larger than the ENux.

Correlation between EN Amplitude and EDA Increase

In an attempt to see whether the size of both EN amplitudes is correlated with an increase in EDA, mean ENs were calculated for each subject, as well as the increase in EDA response to unexpected and very unexpected events, compared to expected events. If the ENs are directly responsible for the increase in EDA, then significant correlations ought to be observed. However, there was no significant correlation between the size of the EN and the EDA ($r = -.342$, $p = .322$).

Positive Components

Although these were not hypothesized, several positive components were found: a large and globally distributed

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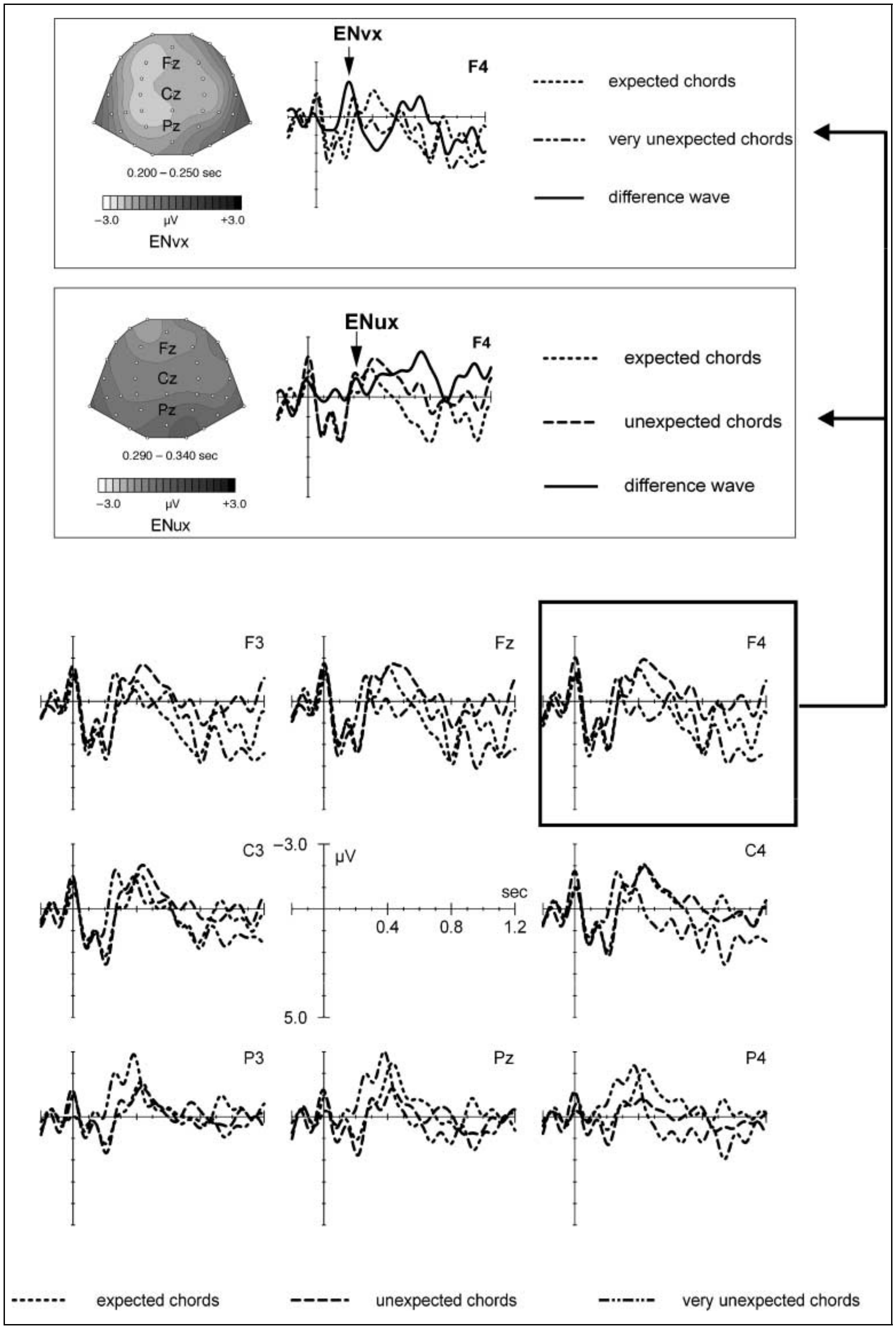
Figure 7. ERP responses to harmonic expectancy violations for nonmusicians. ERPs to all three harmonic conditions are displayed at the bottom. Arrows from the F4 electrode point to displays of the difference waves between the expected and one of the unexpected conditions (top: very unexpected − expected = ENvx; bottom: unexpected − expected = ENux) and their distributions over the scalp (interpolated over the indicated time windows).



one for musicians in response to the very unexpected harmonic event (Neapolitan Chords) peaking at around 340 msec strongest over the central electrodes, and another peaking at 470 msec strongest over the parietal electrodes. Nonmusicians also showed a slight positivity between 300 and 500 msec on the right hemisphere in response to the very unexpected chords. This positivity was also observed in response to merely unexpected chords (Bach original), but only at right parietal sites.

An ANOVA with factors chord type (expected, very unexpected), anterior/posterior, and training for all electrodes for the time window 300–400 msec revealed a significant effect of chord type [$F(1,11) = 16.84$, $p < .005$], but no interaction with the factor anterior/posterior. There was, however, an interaction of chord type and training [$F(1,22) = 8.24$, $p < .01$].

Another ANOVA with factors chord type (expected, very unexpected), training and anterior/posterior in the

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time window 400–500 msec revealed a significant effect of chord type [$F(1,11) = 31.05, p < .0002$] as well as a significant interaction for factors chord type and anterior/posterior [$F(1,11) = 8.24, p < .05$, showing that it was larger over parietal sites] and for factors chord type and training [$F(1,22) = 12.69, p < .005$].

An ANOVA for nonmusicians with the factor chord type (all three) over right parietal electrodes revealed a significant effect [$F(2,22) = 4.01, p < .05$]. Subsequent comparisons between conditions, however, revealed no significant differences when Bonferroni-corrected.

Although the P3 has been associated with arousal (Polich & Kok, 1995), the data do not warrant the need for a correlation between P3 size and EDA because the P3 was found only in response to very unexpected chords, whereas the EDA varied systematically with both mildly and very unexpected chords.

DISCUSSION

Continuous Responses

The behavioral part of the present study found significant effects of harmonic expectancy violations on both the local perception of tension in music (as recorded continuously during the presentation of the chorales), as well as on the emotional impact of the music (as rated at the end of each piece). The harmonic expectancy violations consisted of only one chord, and it is therefore particularly striking that perceived tension and the overall emotional impact of a musical piece can be mediated by as little as one specific musical event. Participants were not informed about the presence of harmonic irregularities and were not required to detect those chords, hence, observable effects are not attributable to task requirements.

Local emotionality did not increase with heightened harmonic unexpectedness, possibly because harmonic expectancy violations are capable of influencing the perception of local tension fluctuations only, rather than leading to an immediate locally related emotional response. The increase of both the perception of tension in music and the overall emotional impact has been observed in previous studies (Krumhansl, 1997) and may suggest that tension is one possible factor involved in increasing the overall emotional impact.

Physiological Measures

The physiological measures provide data which complement the subjective responses. EDA response, a measure typically viewed as indicating autonomic arousal, was found to increase with harmonic unexpectedness.

The IBI, on the other hand, did not increase, and because this measure has been associated strongly with the processing of the valence of stimuli, it suggests that harmonic expectancy violations lead only to an increase in arousal, rather than bearing on the valence of the emotional experience. It could, however, also be that particular physiological measures are suited only to particular features of musical stimuli. Heartbeat measurements may not be sensitive to single chord changes, although such changes could be emotionally valent to the listener.

Our findings suggest the possibility of a causal chain whereby the perception of tension leads to an increase in arousal, which in turn predisposes to an increase in overall emotionality ratings. The observable absence of changes in local emotionality and valence (as suggested by an absence of IBI changes) supports this interpretation. A recent study by Dibben (2004) demonstrated the influence of peripheral feedback in the emotional experience. In her study, the emotional intensity experienced by music listeners was directly influenced by their arousal state, suggesting that bodily states are at least partly used as information for listeners about their emotional state. This would provide a link between the increased arousal and overall emotionality.

It is surprising that clear emotion-related subjective and physiological effects could be elicited by stimuli which were synthesized electronically and possessed none of the other expressive attributes normally inherent to human performance (e.g., variations in tempo and loudness). This provides some reassurance that these effects are robust and can be extended to a range of types of musical stimuli.

The absence of any differences between musicians and nonmusicians in the subjective and physiological indices of emotion suggests that the perception and feeling of emotion in response to music appears not to be mediated by expertise, as echoed in the literature (see Bigand & Poulin-Charronnat, in press).

Early Negativities

The EEG data showed a negative effect resembling the ERAN in time course and partially in scalp distribution in response to very unexpected harmonies (ENvx), as well as a similar negativity in response to merely unexpected harmonies (ENux). Neither the ENvx nor the ENux were lateralized significantly, but distributed broadly over the scalp. However, for several reasons discussed below, the authors believe these components to reflect the same cognitive function as the ERAN found in previous studies (Koelsch et al., 2000), namely, the processing of harmonic expectancy violations.

The fact that the scalp distributions of the present data do not completely match with those described in previous studies should not be a surprise. The lateralization of the ERAN has been previously shown to be somewhat inconsistent (Koelsch, Maess, Grossmann, & Friederici, 2003) and previous neuroimaging studies (Maess, Koelsch, Gunter, & Friederici, 2001; Koelsch,

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Gunter, Friederici, et al., 2002) suggest that the neural generators of the ERAN are located in both the left and the right hemispheres (in the inferior part of BA 44). We assume that the lateralization of the ERAN becomes weaker with the increasing musical complexity of musical stimuli, however, systematic research is still needed in this area. The present findings therefore support previous studies in this field, which indicate that ENs, notably the ERAN, are sensitive to expectancy violations (Koelsch, Maess, et al., 2003; Koelsch et al., 2000).

It is noteworthy that an EN was found in response to unexpected harmonies, which were originally composed that way. In contrast, the ERAN reported previously in response to real musical stimuli (Koelsch & Mulder, 2002) was the result of the authors' deliberate harmonic manipulation of a more expected original within the composition.

The finding that the ENvx appears to be larger than the ENux supports the notion that these negativities are sensitive to the degree of harmonic distance because the stronger music-syntactic irregularity (Neapolitan Chord) elicited a larger negativity than the milder irregularity. This is consistent with several previous studies comparing the amplitude of the ERAN with the extent of the harmonic expectancy violation (Koelsch, Jentschke, & Sammler, submitted; Koelsch, Gunter, Friederici, et al., 2000).

Integrating the ERPs and the physiological and subjective indicators of emotion does not provide a clearcut picture. The correlation analysis between the event-related negativities and the EDA was not significant, possibly due to too much intra- and interindividual variance. However, both electrodermal response and EN amplitudes increased with increasing harmonic irregularity. It would appear that the detection of an irregular event is a prerequisite for an emotional response. Thus, the generation of the EN appears to give rise to subsequent emotional activity (see also Koelsch & Siebel, 2005). It is unlikely that the EN could directly reflect the emotional response because early anterior negativities elicited in response to harmonic irregularities are mainly generated in the fronto-opercular cortex and not in the limbic or paralimbic cerebral structures (Koelsch et al., 2005).

Positive Components

Several positive components were observed in the present study which were also previously reported in the literature on the processing of harmonic expectancies. Musicians showed an earlier, more fronto-centrally distributed and a later, more parietally distributed positivity (340 and 470 msec, respectively) in response to very unexpected harmonies. Nonmusicians tended to show a similar pattern, but with considerably smaller amplitudes, and with a slight right-lateralization of the parietal positivity.

Notably, these positivities were elicited even though chords were not task-relevant in the present study. We assume that the earlier positivity reflects attentional mechanisms (such as an involuntary shift of attention due to the potential relevance of a perceived stimulus; Escera, Alho, & Schroger, 2000). The later positivity is reminiscent of P300-like positivities elicited during the processing of musical information, which have been previously reported by both Regnault, Bigand, and Besson (2001) and Janata (1995), presumably reflecting processes of structural analysis that have been reported to often follow the detection of harmonic irregularities (Koelsch & Siebel, 2005). This positivity was found only in musicians and only in response to very unexpected harmonic events, which are not only harmonically unrelated but also stylistically irregular, and is never featured in genuine works by the composer.

Time Course

Further differences between musicians and nonmusicians were found in the processing speed of the ENs, but not in the amplitude size. Musicians seemed to process both very expected and mildly unexpected harmonic events faster than nonmusicians. This suggests that musical training enhances harmonic processing, in line with results from previous studies (Koelsch, Schmidt et al., 2002; Besson, Faita, & Requin, 1994). This implies that musicians are more fluent at processing music-syntactic information (although it has been shown that nonmusicians also have a strong sense of music-syntactic regularities; Bigand, Poulin, Tillmann, Madurell, & D'Adamo, 2003; Koelsch, Schmidt, et al., 2002). This would make sense in the light of the increased exposure to music, in both playing and listening, which as a result may facilitate processing of music-syntactical irregularities.

Conclusion

The present data show that music-syntactically irregular chords elicit brain responses related to the processing of musical structure (i.e., early anterior negativities), and also trigger processes related to the processing of emotional stimuli, as indicated by the systematic increase in EDA. Earlier latencies of the ENs for musicians indicate enhanced processing abilities of harmonic expectancy violations compared to nonmusicians. Also, a larger parietal positivity for musicians suggests a functional sensitivity of this component to stylistic violations within pieces of Western classical music. Additionally, the present data support Meyer's (1956) claim that musical emotions may arise through the suspension and fulfillment of expectations. Due to the absence of local emotionality changes, however, it would be more accurate to say that harmonic unexpectedness *predisposes* the listener to increases in emotionality, as indicated by a global increase in subjective emotionality. This was

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supported by the psychophysiological data, which suggest that harmonic expectancy violations are capable of increasing the arousal of the listener. A systematic positive relationship between the perception of musical tension and harmonic unexpectedness supports a previously observed link between musical tension and emotion (Krumhansl, 1997).

The present data provide evidence in support of the role of musical structure in the listener's emotional experience. The early neural processing of harmonic expectancy violations may trigger a cascade of processes, eventually reflected in increased arousal levels, which in turn may lead to heightened perception of overall emotionality.

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