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Distortion and Western Music Chord Processing: An ERP Study of Musicians and Nonmusicians

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Guitar distortion used in rock music modifies a chord so that new frequencies appear in its harmonic structure. A distorted dyad (power chord) has a special role in heavy metal music due to its harmonics that create a major third interval, making it similar to a major chord. We investigated how distortion affects cortical auditory processing of chords in musicians and nonmusicians. Electric guitar chords with or without distortion and with or without the interval of the major third (i.e., triads or dyads) were presented in an oddball design where one of them served as a repeating standard stimulus and others served as occasional deviants. This enabled the recording of event-related potentials (ERPs) of the electroencephalogram (EEG) related to deviance processing (the mismatch negativity MMN and the attention-related P3a component) in an ignore condition. MMN and P3a responses were elicited in most paradigms. Distorted chords in a nondistorted context only elicited early P3a responses. However, the power chord did not demonstrate a special role in the level of the ERPs. Earlier and larger MMN and P3a responses were elicited when distortion was modified compared to when only harmony (triad *vs.* dyad) was modified between standards and deviants. The MMN responses were largest when distortion and harmony deviated simultaneously. Musicians demonstrated larger P3a responses than nonmusicians. The results suggest mostly independent cortical auditory processing of distortion and harmony in Western individuals, and facilitated chord change processing in musicians compared to nonmusicians. While distortion has been used in heavy rock music for decades, this study is among the first ones to shed light on its cortical basis.

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Key words: chord, musicians, distortion, harmony, cortical auditory processing

Guitar distortion has been intentionally and increasingly used in rock music to alter the guitar sound since the 1960s. Distortion is a nonlinear effect, which compresses the audio signal, causing longer decay-time of tones and lifts the noise-floor due to increased gain (Bloch, 1953; Dutilleux & Zölzer, 2002; Rossing, Moore, & Wheeler, 2002). Harmonic distortion enhances the natural harmonic series, i.e., frequency components that are integer multiples of a fundamental tone. Distortion also generates new intermodulation frequency components, i.e., combination tones, whose frequencies are given by subtraction and multiplication of any two frequency components (Benade, 1976; Helmholtz, 1877/1954; Rossing et al., 2002). Thus, the harmonic content of a distorted chord is notably more complex than the fingering on the guitar fretboard would indicate. Combination tones were considered a perceptual rather than an acoustic feature (Berger & Fales, 2005), but have been shown to be an acoustic feature in a more recent study: not only does the listener perceive the additional harmonic partials, but they appear in the acoustic signal (Lilja, 2009).

A power chord is created by a distorted interval of the fifth (Lilja, 2009). Without distortion the fifth sounds plain or "open": a two-tone chord (i.e., dyad) contains no interval of the third as a three-tone chord (i.e., triad) would. The fifth without distortion contains only harmonic partials of the constituent tones, whereas due to harmonic distortion, a power chord also contains a significant amount of partials not present in the individual tones of the interval. In the power chord A2-E3, these combination tones are on, e.g., 55 Hz (distortion component *d1*), 275 Hz (*d2*), and 385 Hz (*d3*), which are equal to the musical pitches an octave below (*A1*) the original root tone, an octave plus a major third (*C♯4*) above the original root tone, and an octave plus a minor seventh (*G4*) above the original root tone (Lilja, 2009, 2015; illustrated in Figure 1). Thus, although the power chord is fingered as a dyad, acoustically it is a major

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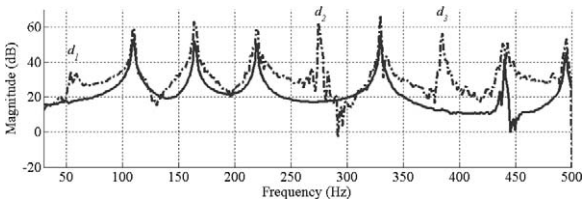


FIGURE 1. Magnitude spectrum of a dyad A2-E3 on the electric guitar without (solid line) and with distortion (dashed line) (Lilja, 2009).

chord. This phenomenon is easy to perceive aurally (Lilja, 2015), and certainly guitar players have been aware of this. For instance, Pete Townshend of the rock band The Who states that "none of the shapes that I play with loud distortion have a 3rd, because you hear the 3rd in the distortion" (Resnicoff, 1989).

Many studies on music processing have recorded change-related event-related potentials (ERPs) with electroencephalogram (EEG) to examine the auditory system in the cortical level. The mismatch negativity (MMN) is a fronto-centrally maximal negative-polarity response in the ERP waveform around 100-250 ms after deviance onset that reflects a mismatch between the heard and the expected stimulus (Kujala, Tervaniemi, & Schröger, 2007; Näätänen, Paavilainen, Rinne, & Alho, 2007; Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001). Larger deviance in the sound stream tends to elicit larger MMN responses and may also cause the MMN to peak earlier (Amenedo & Escera, 2000; Jaramillo, Paavilainen, & Näätänen, 2000; Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004; Pakarinen, Takegata, Rinne, Huotilainen, & Näätänen, 2007; Tiitinen, May, Reinikainen, & Näätänen, 1994). The P3a response is a later fronto-central positive-polarity response to an unexpected stimulus in passive listening conditions, thought to reflect involuntary attention switching towards the stimulus and updating of working memory (Alho et al., 1998; Escera & Corrall, 2007; Horváth, Winkler, & Bendixen, 2008). P3a amplitude is also sensitive to deviance magnitude (Ford, Roth, & Kopell, 1976; Novitski et al., 2004).

In recent years, the MMN has been increasingly utilized to study processing of Western music chords in adults (Brattico et al., 2009; Tervaniemi, Sannemann, Nöyränen, Salonen, & Pihko, 2011; Virtala et al., 2011; Virtala, Huotilainen, Partanen, & Tervaniemi, 2014) and children (Putkinen, Tervaniemi, Saarikivi, Ojala, & Huotilainen, 2014; Virtala, Huotilainen, Partanen, Fellman, & Tervaniemi, 2013; Virtala, Huotilainen, Putkinen, Makkonen, & Tervaniemi, 2012). In these studies, pre-attentive readiness for major vs. minor chord discrimination as evidenced by MMN elicitation has been demonstrated in Western children and adults with and without formal music training, and tentatively even in newborns. Newborn infants demonstrated a small negative MMN to minor chords among major chords and a wide positive mismatch response to dissonant chords presented among consonant chords, indicating readiness for chord processing early on (Virtala et al., 2013).

As cognitive neuroscience of music has demonstrated, music expertise is associated with enhanced processing of music-related stimuli, categories, and regularities (see e.g., Moreno & Bidelman, 2014; Pantev & Herholtz, 2011). Music training and expertise have been associated with facilitated major-minor processing, as evidenced by enlarged MMN responses (Putkinen et al., 2014; Tervaniemi et al., 2011; Virtala et al., 2011, 2014). Virtala and colleagues (2014) demonstrated that chord-MMN amplitude recorded in an ignore condition also correlated with behavioral detection accuracy, thus indicating that MMN amplitude can reflect perceptual skills. MMN studies on processing mistuning and dissonance in chords have also demonstrated facilitated processing in musicians, as indicated by elicitation of the MMN only in musicians (Koelsch, Schröger, & Tervaniemi, 1999) or larger MMN responses in musicians than non-musicians (Brattico et al., 2009). Furthermore, contour and interval changes in a melody elicit larger MMNm responses (magnetic counterparts of the MMN recorded with magnetoencephalogram, MEG) in musicians than nonmusicians (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004). For the P3a response, plasticity induced by music expertise has been demonstrated for violations of Western music harmony that elicited enhanced P3a responses in folk musicians compared to nonmusicians (Brattico, Tupala, Glerean, & Tervaniemi, 2013; see also Tervaniemi, Janhunen, Kruck, Putkinen, & Huotilainen, 2015). Similarly, changes in interval width between consecutive notes in a melody elicited earlier and larger P3a responses (and later P3b responses) in musicians than nonmusicians (Trainor, Desjardins, & Rockel, 1999). In addition to amplitude, response latency can be sensitive to effects of music training. For example, musicians show shorter MMN and P3a latencies than nonmusicians in response to frequency changes in harmonic tones (Nikjeh, Lister, & Frisch, 2009).

Cortical processing of chords and plasticity associated with music training are thus reflected in both MMN and P3a responses, both responses being earlier and/or stronger in musicians than nonmusicians. However, since many of the ERP studies on music processing have been conducted with sinusoidal sounds instead of

harmonically rich, natural music sounds, the ecological validity of the obtained results may be limited. Tervaniemi and colleagues (2000) demonstrated that presenting harmonically rich sounds instead of sinusoidal sounds may facilitate pitch-change processing as evidenced by ERPs (see also Novitski et al., 2004; however Virtala et al., 2014, found no differences in the MMN responses to chords composed of sinusoidal sounds or authentic piano tones). Also, it has been reported that processing complex vs. simple sounds may have different generators in the auditory cortex (Alho et al., 1996). Distortion largely affects the harmonic structure of chords, and it is likely that it modifies the cortical ERPs as well (e.g., in the level of activity sources or response latency and magnitude). However, to our knowledge, distortion in chords has not been studied in neuroscientific experiments on music processing. In a behavioral study, Juchniewicz and Silverman (2013) investigated the tonal perception and restoration of thirds in terminal chords of electric guitar chord progressions with and without the thirds in clean-tone and distorted conditions. They found significant interaction between chord sequences, distortion, and types of chords used in the progressions, and it appeared the unique properties of each sequence affected the perception of the terminal chords. However, their participants did tend to perceive the thirdless terminal chords as more major than minor in progressions with distortion and when the other chords were lacking thirds as well. This finding is in line with the results by Lilja (2009), which demonstrated that distortion produced a major third in otherwise thirdless chords.

The aim of the present study was to explore how changes in the level of distortion and harmonic structure of a chord affect its cortical auditory processing in Western listeners, and how music expertise modifies these processes. The objective was to gain pioneering information on the neural basis of distortion processing in typical Western individuals, and to compare groups with no notable formal music training and with expert levels of music training. To this end, experimental paradigms were constructed where four-tone electric guitar chords with or without distortion and with or without the major third (i.e., triads or dyads) were presented. The paradigms had an oddball design where one of the chords served as a repeating standard stimulus and other chords served as occasional deviant stimuli, in order to record MMN and P3a responses related to deviance processing. Paradigms were presented to musician and nonmusician participants in an ignore condition.

While nondistorted chords without the major third are dyads and nondistorted chords with the major third are major triads, the situation is harmonically more complex for distorted chords. As introduced above, distortion changes the dyad into a major chord (Lilja, 2009), while a distorted major triad is still a major triad. Based on the acoustical and perceptual properties of the power chord, it was hypothesized that distorted dyads would be represented in the auditory system similarly to *major chords*, including the perception of the major third. As an acoustic phenomenon, we expected this to happen independent of the participants' music background. In the level of the change-related ERPs, this would be visible as small and/or late MMN and P3a responses in paradigms where distorted dyads appear in the context of (distorted and nondistorted) major triads (and also in the opposite condition, when major triads appear among distorted dyads). In contrast, distorted dyads or (distorted and nondistorted) triads in the context of nondistorted dyads (and in the opposite condition) would demonstrate larger and/or earlier MMN and P3a responses due to the difference between their harmonic structures (no major third in the nondistorted dyad). Also, accordingly, distorted triads among nondistorted triads (and vice versa) would demonstrate rather small/late MMN and P3a responses because of their similar harmonic structure. Due to the exploratory nature of the study, no separate hypotheses were set for MMN and P3a elicitation and size. As MMN responses are elicited by detectable changes in the auditory stream (Näätänen et al., 2007), and P3a responses are elicited particularly by salient or unexpected deviants (Alho et al., 1998, Escera & Corrall, 2007), we expected at least MMN responses to be elicited by all chord contrasts. Additionally, based on previous findings (Brattico et al., 2009, 2013; Koelsch et al., 1999; Putkinen et al., 2014; Tervaniemi et al., 2011; Trainor et al., 1999; Virtala et al., 2014), we expected generally facilitated chord processing as evidenced by larger and/or earlier MMN and P3a responses in musicians compared to nonmusicians.

Method

PARTICIPANTS

Twenty-eight participants recruited from local universities and music academies volunteered in the present experiment (13 male, mean age = 23, range = 19-34). An additional five participants took part in the experiment, but their data were excluded from analysis due to continuous tinnitus in one participant and interrupted recordings in four participants. According to their own report, all included participants were right-handed and had no problems related to hearing, language, or basic

motor functions. In order to further study the effect of music expertise on chord processing, the participants were divided into two groups, one with expert levels of music training and the other with a maximum of 2 years of prior formal music training in addition to general music classes in school. Two participants were omitted in this phase because they fell between the two groups in their amount of music training. Thus, 13 musicians (7 male, mean age = 23 years, range = 19-32 years) and 13 nonmusicians (6 male, mean age = 24 years, range = 19-34 years) were included in the group comparisons in the present study. The musician and nonmusician groups did not demonstrate differences in their level of completed education, $F(1, 24) = 0.59$, $p > .10$ (one-way ANOVA with four levels: elementary school, upper secondary school, bachelor's degree, master's degree).

In the musician group, the mean starting age of first instrument was 6 years ($SD = 2.7$, range = 3-12), the total amount of formal training was 17 years ($SD = 2.9$, range = 12-21), and the current amount of daily practice was 3.3 hours ($SD = 1.4$, range = 0.5-5.0). The longest-practiced instruments among the musicians were piano and violin (4 players of each), contrabass (1), guitar (1), bassoon (1), singing (1), and saxophone (1). All of the musicians had ear training (solmization, sol-fa etc.) as a part of their music education for 8 years on average ($SD = 3.7$, range = 2-14). No one reported having absolute pitch. Ten of the 13 musicians reported playing mostly classical music as opposed to other music genres.

All participants gave written informed consent to participate in the present study and received a participation fee (vouchers for cultural or exercise activities) after completing the study. This study received ethical approval of the University of Helsinki Review Board in Humanities and Social and Behavioural Sciences.

COGNITIVE ABILITIES

Possible differences in general cognitive abilities between the musicians and nonmusicians were studied by presenting the participants with parts of the Wechsler Intelligence Scale (WAIS-III, subtests: Similarities, Symbol search, Digit span, and Block design, Wechsler, 1997a) and the Wechsler Memory Scale (WMS-III, subtests: Logical memory I-II, Paired associates I-II, and Faces I-II, Wechsler, 1997b) as well as the Trail-Making Test A and B. The subtests measure linguistic and visual reasoning as well as visuo-motor skills, working memory, linguistic and visual memory, executive functions, and processing speed. One-way ANOVAs showed superior performance in the nonmusician group in verbal tasks, namely, Logical memory I, $F(1, 22) = 5.30$, $p < .05$ (nonmusicians mean 13.3 vs. musicians mean 11.5), Logical memory II, $F(1, 22) = 4.44$, $p < .05$ (13.7 vs. 12.0), and Similarities, $F(1, 23) = 15.24$, $p < .01$ (13.5 vs. 11.5). These group differences may be related to the more literary study fields (e.g., humanities or social sciences instead of music) of the nonmusician participants. The other subtests did not demonstrate group differences.

EXPERIMENTAL STIMULI AND PARADIGM

The auditory stimuli consisted of natural-like electric guitar chord sounds synthesized in 44.1 kHz, 16-bit samples with the Logic Pro 9 audio sequencing software using an onboard software guitar synthesizer ("Twangy Electric"), guitar amplifier simulator ("Guitar Amp Pro", with the setting "British Clean"), speaker simulation ("UK 1*12") and the built-in OSX Core Audio hardware. Further effects were by-passed. The sounds produced were 500 ms in duration, with a natural-like, short 2 ms attack and ending with a 50 ms fade-out ($1/x^2$). Two chords with four tones with equal MIDI key velocities were synthesized: a D-major triad chord with the pitch content of D2–A2–F♯3–A3 and a dyad chord, i.e., a two-tone chord without the major third, with the pitch content of D2–A2–D3–A3. Pure tuning ("Hermode classic 3/5-all") was used (as opposed to, e.g., equal-temperament), corresponding to fundamental frequencies of 73.3–110–183.3–220 Hz and 73.3–110–146.7–220 Hz, and fundamental ratios of 2:3:4:6 and 2:3:5:6, respectively (A4 = 440 Hz). The four-part voicing was used to ensure voicing natural to the electric guitar and to minimize the effect of melodic changes in the top voice. The distorted versions of the chords were created using the distortion effect of the Logic Pro software, set to produce a 48 dB harmonic distortion (e.g., Lilja, 2009; Rossing et al., 2002). The sound files were normalized to -10.0 dB RMS to guarantee equal RMS power across sounds and to avoid digital clipping. The four stimuli are presented in Figure 2.

The auditory stimuli were presented in oddball paradigms where one of the chords acted as a repeating standard stimulus with a probability of 70% and the remaining three chords served as occasional deviant stimuli (probability of 10% each). Four paradigms were constructed, one for each stimulus as the standard. Each paradigm consisted of 1,001 stimuli (99 or 100 per deviant type) introduced in a pseudo-random order so that at least one standard preceded every deviant. The time from the beginning of the stimulus until the beginning of the next stimulus was 500 ms (with no silent gap between the stimuli), and the duration of each paradigm was approximately 8.3 minutes.

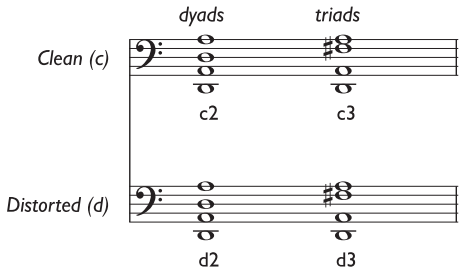


FIGURE 2. The four stimuli: dyads (pitch content D2–A2–D3–A3) vs. triads (pitch content D2–A2–F♯3–A3), both nondistorted (clean) vs. distorted. The four-tone voicing was used to minimize the effect of melodic changes in the top voice while ensuring voicing natural to the electric guitar.

EXPERIMENTAL PROCEDURE

The experiment (four paradigms in random order) was presented to the participants as the second part of a 1 h 15 min long recording session, after a coffee break. The data collected during the first part of the recording session has been reported elsewhere, including mostly the same participants (Virtala et al., 2014). During the EEG experiment, the participant watched a self-chosen DVD movie without sound and was advised not to move or blink a lot and not to pay attention to the sounds. The participant sat in a comfortable chair in a soundproof, electrically shielded chamber, while the experimental paradigms were introduced via headphones (Sony Dynamic Stereo Headphones, MDR-7506) with a sound level of 65 dB SPL(a).

EEG RECORDING AND ANALYSIS

The EEG was recorded continuously from 64 electrodes (headcap and amplifier: Biosemi ActiveTwo, mk1, BioSemi B. V., Amsterdam, The Netherlands) placed according to the international 10–20-system, with additional 5 external Ag/AgCl electrodes (right and left mastoid behind the ears, vertical and horizontal electro-oculogram below and next to participant's left eye, tip of the nose) with an online sampling rate of 512 Hz. The EEG was imported to the BESA analysis program (v 6.0, BESA GmbH, Gräfelfing, Germany), filtered at 1–30 Hz (slope 12 dB/oct, zero phase) and re-referenced to the mean of the mastoid electrodes. Automatic eye artifact removal was conducted (v6.0, BESA, Berg & Scherg, 1994). The data were divided to epochs (-100–500 ms) with a pre-stimulus baseline of 100 ms, and averaged separately for each individual, stimulus type and electrode in each part of the experiment. All epochs with voltage changes exceeding ± 120 μV were omitted from further analysis. After this, the amount of accepted standard epochs was more than 75% in all participants in each paradigm. A baseline correction for -100–0 ms was applied for all epochs prior to statistical testing.

TABLE 1. *The 12 Stimulus Contrasts*

Name	Description	Type of deviation
c3/d3	nondistorted triad among distorted triads	distortion
c3/d2	nondistorted triad among distorted dyads	distortion + harmony
c3/c2	nondistorted triad among nondistorted dyads	harmony
c2/d2	nondistorted dyad among distorted dyads	distortion
c2/d3	nondistorted dyad among distorted triads	distortion + harmony
c2/c3	nondistorted dyad among nondistorted triads	harmony
d3/c3	distorted triad among nondistorted triads	distortion
d3/c2	distorted triad among nondistorted dyads	distortion + harmony
d3/d2	distorted triad among distorted dyads	harmony
d2/c2	distorted dyad among nondistorted dyads	distortion
d2/c3	distorted dyad among nondistorted triads	distortion + harmony
d2/d3	distorted dyad among distorted triads	harmony

Note: Abbreviations: c = clean sound (nondistorted sound), d = distorted sound, 3 = triad (with the major third interval), 2 = dyad (without the major third interval).

In order to study the responses related to deviance processing, subtraction curves were calculated individually for each participant, electrode, and stimulus contrast, such that the ERP waveform in response to a chord when it acted as the standard stimulus was subtracted from the ERP waveform in response to the same chord when it acted as the deviant stimulus in the context of one of the three other chords (12 contrasts listed in Table 1). This was done because acoustic differences between the four stimulus types are likely to cause differences in the ERP waveform unrelated to deviance detection processes, due to their different spectral composition and rise times (Näätänen & Picton, 1987; for further discussion on the need of experimental control of acoustical sound content, see Schröger & Wolff, 1998, and Jacobsen & Schröger, 2001).

STATISTICAL ANALYSES

Statistical significance of the obtained MMN and P3a responses was analyzed in the midline electrodes Fz, FCz, and Cz, where the responses usually demonstrate largest amplitudes (Kujala et al., 2007). The responses

were deemed statistically significant when one-sample *t*-tests of the mean amplitudes calculated from pre-defined time windows (100–250 ms for MMN, 200–350 ms for P3a) against 0 demonstrated statistical significance ($p < .05$) on at least two out of three midline electrodes (Fz, FCz, and Cz) over groups. A region-of-interest of 21 electrodes (1, 3, 5, z, 2, 4, 6 × F, FC, C) was additionally used to study differences between contrasts, musician and nonmusician groups in mean amplitudes and peak latencies of the responses, and the spatial distribution of the response amplitudes.

For statistical analysis, latencies with the largest MMN and P3a amplitudes were searched from the pre-defined time windows (100–250 ms for MMN, 200–350 ms for P3a) on the 21 electrodes individually for each contrast. Differences in peak latencies between contrasts and groups were analyzed with a repeated measures analysis of variance (ANOVA-R). Based on these results, 40-ms time windows centered around the peak latencies were defined for calculating MMN and P3a mean amplitudes in the different contrasts and groups.

To determine whether there were differences in the response amplitudes between the contrasts, groups or electrode locations (left-right and front-back dimensions), ANOVA-Rs were conducted for the MMN and P3a mean amplitudes on the 21 electrodes and two groups, respectively (within-subjects factors: contrasts, left-right and front-back dimensions; between-subjects factor: group). In the ANOVAs, a Greenhouse-Geisser correction was applied when the assumption of sphericity was violated. In the post hoc comparisons, a Bonferroni correction for multiple testing was applied.

Results

Nondistorted chords in distorted and nondistorted contexts, as well as distorted triads among distorted dyads, elicited MMN responses (Figure 3, Table 2). The MMN responses were earliest and largest for nondistorted among distorted chords, and among them, particularly large for nondistorted triads among distorted dyads and nondistorted dyads among distorted triads (Table 3, Table 4). Scalp distribution of the MMN responses was right-pronounced on frontal electrodes (Figure 6). Distorted chords in a nondistorted context only elicited P3a responses. P3a responses were elicited by all contrasts except for distorted triads among distorted dyads (Figure 3, Table 5). The P3a peaked earlier in contrasts where distortion deviated than when distortion did not deviate (Table 6). When distortion deviated, distorted among nondistorted chords elicited an earlier P3a response than nondistorted among distorted chords. The musicians had larger P3a responses than the nonmusicians (Figure 4). For comparison, the ERPs in response to each deviant plotted against the standard stimulus of that paradigm, instead of the same stimulus as a standard, are presented in Figure 5. All results are presented in detail below.

MMN RESULTS

Statistically significant MMN responses were elicited by all six contrasts with nondistorted chords among distorted or nondistorted chords (c/d and c/c contrasts), whereas distorted among nondistorted chords (d/c) demonstrated positive-polarity responses (same positive response was visible in both the MMN and the P3a latency windows) and of the contrasts with distorted among distorted chords (d/d), only distorted triads among distorted dyads (d3/d2) demonstrated a statistically significant MMN (Table 2).

MMN PEAK LATENCIES: CONTRAST AND GROUP COMPARISONS

MMN latencies differed significantly between contrasts, $F(4, 87) = 24.73$, $p < .001$, $\eta_p^2 = .51$, observed power = 1.0, but there was no main effect of group nor an interaction between contrast and group. Differences between electrodes were not looked for. Distorted among distorted chords and nondistorted among nondistorted chords elicited later MMN responses than nondistorted among distorted chords (d/d and c/c contrasts later than c/d, see Table 3).

For further analysis, MMN mean amplitudes were calculated from the following time windows: 115–155 ms for the early-latency MMN responses to nondistorted among distorted chords, and 145–185 ms for the late-latency MMN responses to distorted among distorted and nondistorted among nondistorted chords.

MMN AMPLITUDES: CONTRAST AND GROUP COMPARISONS AND SPATIAL DISTRIBUTION

MMN amplitudes demonstrated statistically significant differences between contrasts, $F(6, 144) = 34.67$, $p < .001$, $\eta_p^2 = .59$, observed power 1.0, left-right dimension, $F(2, 53) = 89.20$, $p < .001$, $\eta_p^2 = .79$, observed power 1.0, and front-back dimension, $F(1, 28) = 14.01$, $p < .01$, $\eta_p^2 = .37$, observed power = .97, as well as their interaction, $F(4, 87) = 5.03$, $p < .01$, $\eta_p^2 = .17$, observed power 1.0. Interactions between spatial dimensions and contrasts were not looked for. The main effect of group did not quite reach statistical significance, $F(1, 24) = 2.80$, $p = .11$, $\eta_p^2 = .10$, observed power = .36, although numerical values indicated generally larger (more negative) MMN responses in musicians than nonmusicians.

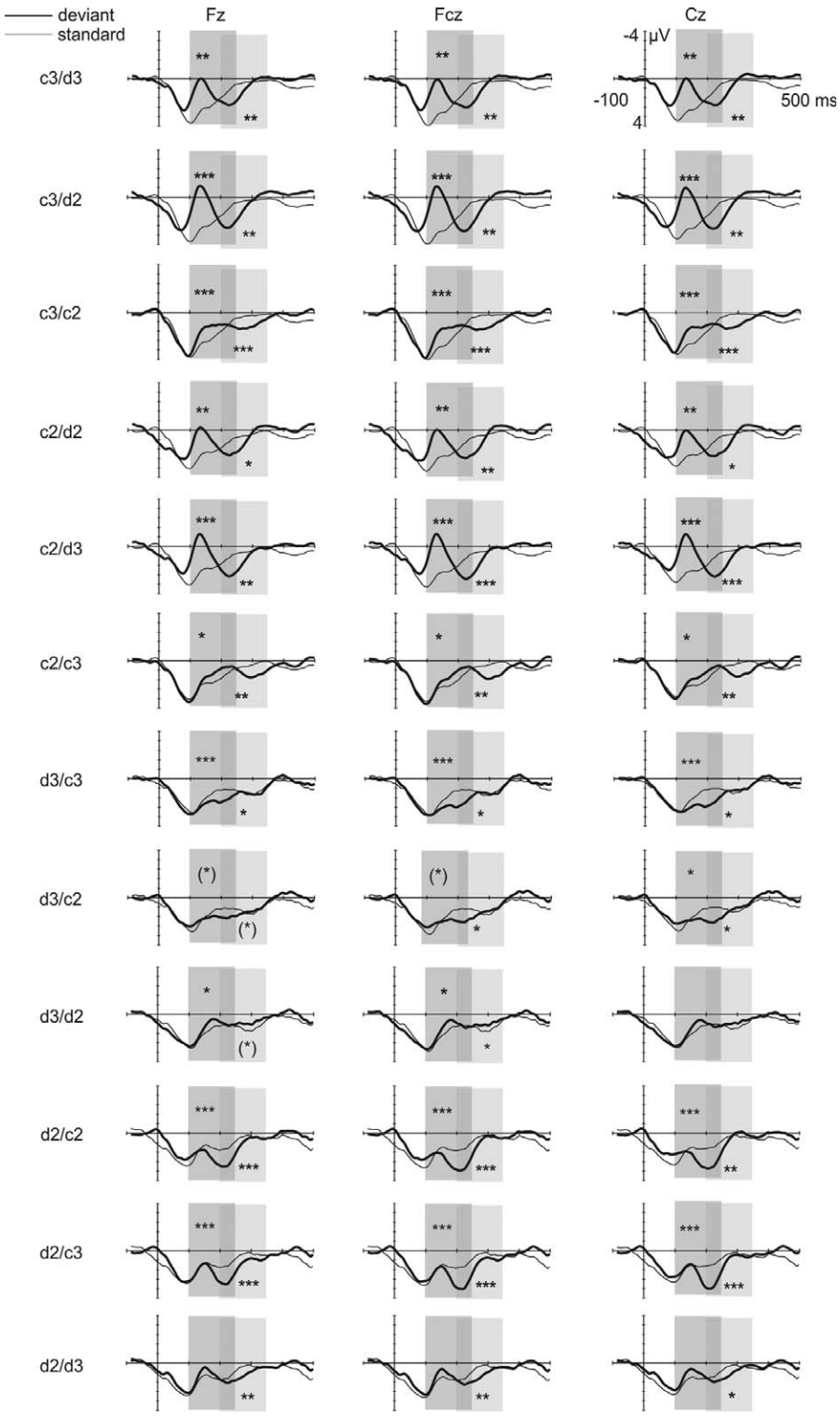


FIGURE 3. Grand-average ERPs on Fz, FCz, and Cz electrodes to the 12 contrasts (abbreviations are explained in Table 1). Thin line illustrates the ERP to the chord acting as the standard; thick line illustrates the ERP to the same chord acting as a deviant in the context of one of the other three chords. Grey bars illustrate the pre-defined MMN and P3a time windows. Time windows demonstrating statistically significant or nearly significant values on *t*-tests are marked with asterisks (*)$p < .10$, *$p < .05$, **$p < .01$, ***$p < .001$.

TABLE 2. *MMN Mean Amplitudes in μV on 100–250 ms Latency Window on Fz, FCz and Cz Electrodes*

	Mean amplitude, μV (std)		
Contrast	Fz	FCz	Cz
c3/d3	**−0.75 (1.02)****	**−0.79 (1.11)****	**−0.74 (1.00)****
c3/d2	**−1.05 (0.63)*****	**−1.09 (0.68)*****	**−0.96 (0.66)*****
c3/c2	**−0.58 (0.63)*****	**−0.66 (0.69)*****	**−0.62 (0.62)*****
c2/d2	**−0.66 (0.95)****	**−0.63 (0.93)****	**−0.54 (0.84)****
c2/d3	**−0.80 (1.05)*****	**−0.87 (1.14)*****	**−0.82 (1.01)*****
c2/c3	**−0.40 (0.85)***	**−0.41 (0.89)***	**−0.38 (0.85)***
d3/c3	0.55 (0.72)***	0.71 (0.82)***	0.77 (0.86)***
d3/c2	0.28 (0.85)(*)	0.38 (1.01)(*)	0.45 (1.10)*
d3/d2	**−0.31 (0.71)***	**−0.30 (0.74)***	−0.22 (0.77)
d2/c2	0.69 (0.77)***	0.83 (0.83)***	0.77 (0.87)***
d2/c3	0.64 (0.70)***	0.79 (0.73)***	0.73 (0.77)***
d2/d3	−0.13 (0.82)	−0.12 (0.91)	−0.20 (0.88)

Note: Standard deviations are in parentheses. Statistically significant *t*-test results (against 0) are marked with asterisks ***$p < .001$, **$p < .01$, *$p < .05$, (*)$p < .10$. Contrasts demonstrating statistically significant MMNs (negative-polarity responses on at least two of three electrodes) are bolded.

Largest MMN amplitudes were elicited by nondistorted dyads among distorted triads and nondistorted triads among distorted dyads (c2/d3 and c3/d2), and smallest by nondistorted dyads among nondistorted triads, nondistorted triads among nondistorted dyads, and distorted triads among distorted dyads (c2/c3, c3/c2 and d3/d2), while nondistorted dyads among distorted dyads and nondistorted triads among distorted triads (c2/d2 and c3/d3) fell between the extremes. Thus, when the deviating feature was distortedness of the chord (c/d contrasts), the MMN responses were larger than when the deviating feature was harmony (c/c and d/d contrasts). MMN amplitudes were largest when both distortedness and harmony were modified at the same time (c3/d2 and c2/d3 contrasts).

The responses demonstrated a typical pattern in the left-right dimension, so that the amplitudes were largest in the midline and were reduced when moving left or right from the midline (in all, $p < .05$, except for 5 vs. 6, 3 vs. 4, 1 vs. 2, and z vs. 2 that did not reach statistical significance). MMN amplitudes were larger on the FCz-row than on the Fz- or the Cz-rows (in both, $p < .01$). Post hoc comparisons of the left-right × front-back interaction revealed that the pattern was different on the F-row, where the responses were more negative on the right F4 than on the left F3 ($p < .01$), and on the right F2 than on the left F1 ($p < .05$), thus suggesting a right-pronounced spatial distribution on the frontal electrodes.

P3A RESULTS

Statistically significant P3a responses were elicited by all contrasts except for distorted triads among distorted dyads (d3/d2, Table 5).

TABLE 3. *MMN Peak Latencies on FCz*

Contrast	Latency, ms (std)	Comparison 1	Comparison 2	Comparison 3	Comparison 4
c3/d3	127.5 (12.6)	< d3/d2***	< c3/c2***	< c2/c3***	
c3/d2	132.9 (13.6)	< d3/d2***	< c3/c2***	< c2/c3***	
c3/c2	165.3 (27.2)	> c3/d3***	> c3/d2***	> c2/d3***	> c2/d2**
c2/d2	140.3 (26.1)	< d3/d2**	< c3/c2**	< c2/c3***	
c2/d3	129.5 (13.8)	< d3/d2***	< c3/c2***	< c2/c3***	
c2/c3	180.3 (36.0)	> c3/d3***	> c3/d2***	> c2/d3***	> c2/d2***
d3/d2	168.9 (31.7)	> c3/d3***	> c3/d2***	> c2/d3***	> c2/d2**

Note: Standard deviations are in parentheses. Results of Bonferroni-corrected post hoc comparisons between contrasts, statistically significant results shown. ***$p < .001$, **$p < .01$, *$p < .05$.

TABLE 4. *MMN Mean Amplitudes on FCz*

Contrast	Amplitude, μV (std)	Comparison 1	Comparison 2	Comparison 3	Comparison 4	Comparison 5
c3/d3	−2.89 (1.81)	< c2/c3***	< c3/c2**	> c3/d2*	< d3/d2***	
c3/d2	−3.76 (1.34)	< c2/d2***	< c2/c3***	< c3/c2***	< c3/d3*	< d3/d2***
c3/c2	−1.35 (1.01)	> c2/d3***	> c3/d3**	> c3/d2***		
c2/d2	−2.29 (1.45)	< c2/d3*	< c2/c3***	< c3/d2***	< d3/d2**	
c2/d3	−3.23 (1.63)	< c2/d2*	< c2/c3***	< c3/c2***	< d3/d2***	
c2/c3	−0.69 (1.27)	> c2/d2***	> c2/d3***	> c3/d3***	> c3/d2***	
d3/d2	−0.75 (1.03)	> c2/d2**	> c2/d3***	> c3/d3***	> c3/d2***	

Note: Standard deviations are in parentheses. Results of Bonferroni-corrected post hoc comparisons between contrasts, statistically significant results shown. ***$p < .001$, **$p < .01$, *$p < .05$, (*)$p < .10$. Note: smaller (more negative) amplitudes indicate larger MMNs.

TABLE 5. *P3a Mean Amplitudes in μV on 200–350 ms Latency Window on Fz, FCz and Cz Electrodes*

	Mean amplitude, μV (std)		
Contrast	Fz	FCz	Cz
c3/d3	**0.51 (0.76)****	**0.56 (0.86)****	**0.45 (0.74)****
c3/d2	**0.60 (0.88)****	**0.68 (0.92)****	**0.60 (0.84)****
c3/c2	**0.56 (0.64)*****	**0.64 (0.64)*****	**0.57 (0.58)*****
c2/d2	**0.40 (0.91)***	**0.47 (0.88)****	**0.43 (0.82)***
c2/d3	**0.73 (1.03)****	**0.77 (1.02)*****	**0.71 (0.87)*****
c2/c3	**0.40 (0.66)****	**0.46 (0.72)****	**0.41 (0.67)****
d3/c3	**0.29 (0.72)***	**0.34 (0.82)***	**0.32 (0.80)***
d3/c2	0.23 (0.70)(*)	**0.30 (0.74)***	**0.32 (0.78)***
d3/d2	−0.33 (0.68)*	−0.24 (0.74)(*)	−0.17 (0.69)
d2/c2	**0.66 (0.72)*****	**0.68 (0.77)*****	**0.51 (0.78)****
d2/c3	**0.84 (0.87)*****	**0.91 (0.95)*****	**0.77 (0.87)*****
d2/d3	**0.42 (0.76)****	**0.48 (0.83)****	**0.35 (0.79)***

Note: Standard deviations are in parentheses. Statistically significant *t*-test results (against 0) are marked with asterisks. ***$p < .001$, **$p < .01$, *$p < .05$, (*)$p < .10$. Contrasts demonstrating statistically significant P3a's (statistically significant positive-polarity responses on at least two of three electrodes) are bolded.

P3A LATENCIES: CONTRAST AND GROUP COMPARISONS

P3a latencies differed statistically significantly between contrasts, $F(10, 240) = 32.54$, $p < .001$, $\eta_p^2 = .58$, observed power = 1.0, but there was no main effect of group nor an interaction between contrast and group. Differences between electrodes were not looked for. When distortion deviated, the P3a peaked earlier than when distortion did not deviate (d/c and c/d contrasts earlier than d/d and c/c contrasts, Table 6). Additionally, distorted dyads among nondistorted dyads elicited an earlier P3a than nondistorted dyads among distorted triads and nondistorted triads among distorted triads (d2/c2 earlier than c2/d3 and c3/d3). Thus, in the contrasts where distortion deviated, distorted among nondistorted chords tended to elicit earlier P3a responses than nondistorted among distorted chords.

For further analysis, P3a mean amplitudes were calculated from the following time windows: 200–240 ms for the early-latency P3a responses to distorted among nondistorted chords, 220–260 ms for the middle-latency P3a responses to nondistorted among distorted chords, and 260–300 ms for the late-latency P3a responses to nondistorted among nondistorted chords and distorted dyads among distorted triads.

P3A AMPLITUDES: CONTRAST AND GROUP COMPARISONS AND SPATIAL DISTRIBUTION

P3a amplitudes differed statistically significantly between contrasts, $F(5, 122) = 3.09$, $p < .05$, $\eta_p^2 = .11$, observed power = .86. There was a statistically significant main effect of left-right dimension, $F(3, 61) = 49.66$, $p < .001$, $\eta_p^2 = .67$, observed power 1.0, and front-back dimension, $F(1, 28) = 4.87$, $p < .05$, $\eta_p^2 = .17$, observed power = .61, and an interaction between them, $F(4, 94) = 5.30$, $p < .01$, $\eta_p^2 = .18$, observed power = .96. Interactions between spatial dimensions and contrasts were not looked for. The main effect of group was statistically significant, $F(1, 24) = 12.32$, $p < .01$, $\eta_p^2 = .34$, observed power = .92, with the musician group demonstrating larger P3a amplitudes than the nonmusician group.

Post hoc comparisons with Bonferroni-corrections revealed that there were no amplitude differences between contrasts that would have reached statistical significance of $p < .05$. The responses demonstrated a typical pattern in the left-right dimension, so that amplitudes were largest in the midline and were reduced when moving left or right from the midline (in all, $p < .05$, except for 5 vs. 6, 3 vs. 4, and 1 vs. 2, that did not reach statistical significance). In the front-

TABLE 6. *P3a Peak Latencies on FCz*

Contrast	Latency, ms (std)	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6	Comp 7	Comp 8
d3/c3	221.2 (41.9)	< c2/c3***	< d2/d3***	< c3/c2***					
d3/c2	218.3 (35.3)	< c2/c3***	< d2/d3***	< c3/c2***					
d2/c2	209.7 (33.2)	< c2/d3*	< c2/c3***	< d2/d3***	< c3/c2***	< c3/d3*			
d2/c3	220.4 (24.8)	< c2/c3***	< d2/d3***	< c3/c2***					
c2/d2	236.7 (35.2)	< c2/c3***	< d2/d3***	< c3/c2***					
c2/d3	236.6 (26.8)	> d2/c2*	< c2/c3***	< d2/d3***	< c3/c2***				
c2/c3	291.8 (49.2)	> d3/c3***	> d3/c2***	> d2/c2***	> d2/c3***	> c2/d2***	> c2/d3***	> c3/d3***	> c3/d2***
d2/d3	264.3 (30.2)	> d3/c3***	> d3/c2***	> d2/c2***	> d2/c3***	> c2/d2***	> c2/d3**	> c3/d3*	> c3/d2***
c3/c2	279.5 (31.8)	> d3/c3***	> d3/c2***	> d2/c2***	> d2/c3***	> c2/d2***	> c2/d3***	> c3/d3***	> c3/d2***
c3/d3	245.5 (26.9)	> d2/c2*	< c2/c3***	< d2/d3*	< c3/c2***				
c3/d2	241.7 (32.0)	< c2/c3***	< d2/d3*	< c3/c2***					

*** = $p < .001$, ** = $p < .01$, * = $p < .05$

Note: Standard deviations are in parentheses. Results of Bonferroni-corrected post hoc comparisons between contrasts, statistically significant results shown. Statistically significant *t*-test results (against 0) are marked with asterisks. ***$p < .001$, **$p < .01$, *$p < .05$.

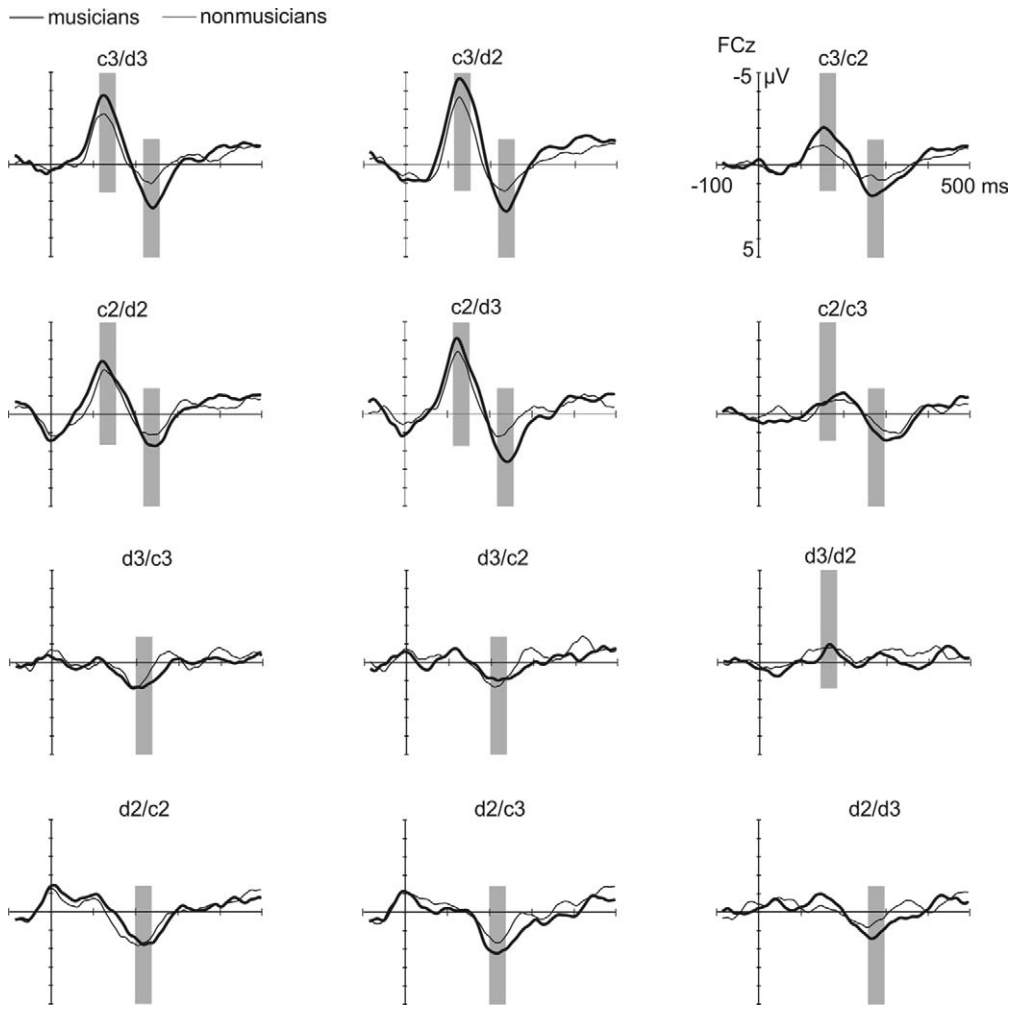


FIGURE 4. Subtraction curves of a chord acting as the standard subtracted from the same chord acting as a deviant in the context of one of the other three chords for the 12 contrasts (abbreviations are explained in Table 1) on FCz electrode. Thin line illustrates the subtraction curve of the nonmusician group; thick line illustrates the subtraction curve of the musician group. Grey bars illustrate the 40-ms time windows used to compare MMN and P3a mean amplitudes between contrasts, groups, and spatial dimensions.

back dimension, P3a amplitudes were larger on FCz than Fz ($p < .001$). Further analysis of the left-right × front-back interaction revealed that the difference between the F row and the FC row reached statistical significance in all electrodes except in the far left (F5 vs. FC5) and far right (F6 vs. FC6). On the left, P3a amplitude was larger on FC5 than C5 ($p < .05$).

Discussion

The present study investigated Western individuals' cortical auditory processing of changes in distortion and harmonic structure in Western music chords and the effect of music expertise on these processes. By far, distortion has not received much interest in music neuroscience, despite its notable role in heavy rock and related music genres. Specifically, we aimed to study the so-called power chord—a distorted fifth interval without the major third that has a special role in heavy rock music. Four electric guitar chords with or without distortion and with the interval of the major third (i.e., triads) or without the interval of the major third (i.e., dyads) were presented to musician and nonmusician participants in a passive EEG experiment in paradigms where each chord acted as a repetitive standard stimulus while the other three chords acted as occasional deviants.

MMN responses were elicited by all contrasts where nondistorted chords were presented among distorted or nondistorted chords, and, additionally, by distorted

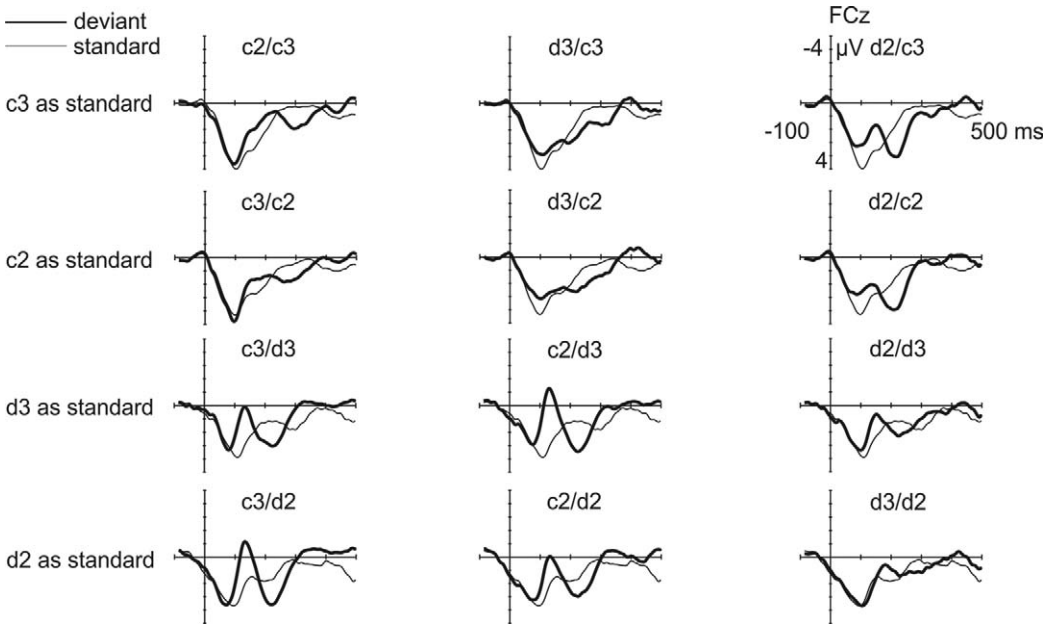


FIGURE 5. Grand-average ERPs on FCz electrode of the 12 contrasts (abbreviations are explained in Table 1). Each deviant stimulus response is plotted against the standard stimulus of the same paradigm, instead of the same stimulus as a standard in another paradigm (as in Figure 3). Thin line illustrates the ERP to the standard stimulus; thick line illustrates the ERP to the deviant stimulus.

triads among distorted dyads. Distorted chords in a nondistorted context did not elicit MMN responses, but they did elicit earlier P3a responses than other contrasts. P3a responses were elicited by all contrasts except for distorted triads among distorted dyads. Thus, while nondistorted chords elicited an MMN response and a P3a response independent of context, distorted chords among nondistorted chords only elicited P3a responses. When distorted chords were presented in a distorted context, the results were mixed. Larger and earlier MMN responses and earlier P3a responses were elicited when distortedness of the chord deviated than when only harmony (triad vs. dyad) deviated. Largest MMN responses were elicited when both dimensions deviated simultaneously. On frontal electrodes, MMN responses demonstrated a right-pronounced spatial distribution over groups. The musician group demonstrated larger P3a amplitudes than the nonmusician group, while the group difference was only tentative for the MMN amplitude and absent for the MMN and P3a peak latencies.

Table 7 presents an overview of the original hypotheses and the obtained results. According to the hypotheses, distorted dyads (i.e., power chords) would be treated in the auditory system as major chords, and thus they should elicit large and early MMN and P3a responses when presented in the context of nondistorted dyads but small and late responses in the context of triads. Our hypothesis was based on the acoustic and perceptual properties of the power chord (Lilja, 2009). However, this hypothesis was mainly not supported by the obtained results. Only seven of the 25 contrasts listed in Table 7 demonstrate results that are in line with the hypotheses, while 11 were against the hypotheses. Rather, the present findings are in line with prior neurophysiological evidence on general auditory mismatch processing, reviewed below.

The obtained result that a change in the distortedness of the chord (distorted vs. nondistorted) elicited larger and earlier change-related responses than a change in the harmonic structure (dyad vs. triad) is in line with previous research demonstrating larger and earlier MMN and P3a responses to perceptually larger deviants (Ford et al., 1976; Jaramillo et al., 2000; Novitski et al., 2004; Pakarinen et al., 2007). Varying the level of distortion in the chords clearly causes a large perceptual contrast evident in the auditory signal waveform, compared to the more subtle change elicited by a change in the harmonic structure (e.g., adding or omitting the third interval). Also, a simultaneous deviance in the distortion and harmony of the chord introduces a double deviant that elicits larger responses than deviance in a single dimension of the sound (Levänen, Hari, McEvoy & Sams, 1993; Paavilainen et al., 2003; Paavilainen, Valppu, & Näätänen, 2001; Schröger, 1995; Takegata, Paavilainen,

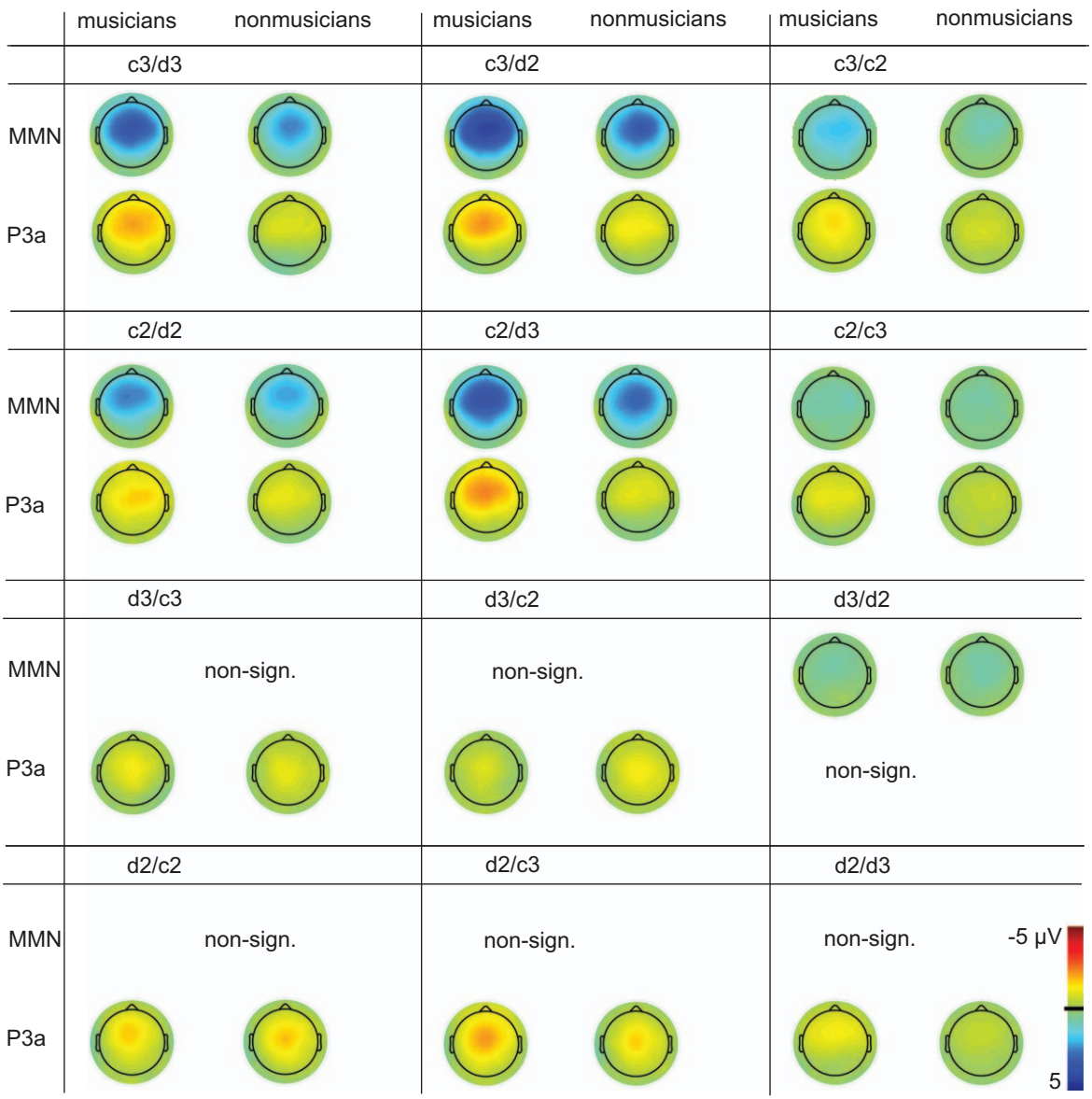


FIGURE 6. Head figures illustrating scalp distributions of the statistically significant MMN and P3a mean amplitudes in the musician and nonmusician groups. (See color version of figure online)

Näätänen & Winkler, 1999, 2001; Wolff & Schröger, 2001). While the MMN mean amplitudes on FCz (demonstrating largest values) to double deviants were -3.72 and -3.15 microvolts, amplitudes to single-deviants were -2.80 and -2.28 microvolts for contrasts where distortion deviated and -1.32, -0.62, and -0.69 microvolts for contrasts where harmony deviated. Average single-deviant amplitudes add up to -3.4 microvolts, equal to the mean of double deviant amplitudes. Thus, it seems that the size of the MMN amplitude in response to double deviants is the sum of the MMN amplitudes in response to each single deviant. Previous research has suggested that this additivity indicates that the two deviance dimensions are processed by different neural populations (Paavilainen et al., 2003; Schröger, 1995; Wolff & Schröger, 2001). Thus, our results give support to considering distortion and harmony as independent, orthogonal features in the auditory system.

Context had an effect on chord change processing in the present study. While nondistorted chords in a distorted context elicited MMN and P3a responses, distorted chords in a nondistorted context did not elicit

TABLE 7. *Result Overview*

	Contrasts					
ERP parameters	c3/d3	c3/d2	d3/c3	d3/d2	d2/c3	d2/d3
Hypothesis: small and late						
MMN latency	early	early	.	*late*	.	.
MMN amplitude	middle	large	.	*small*	.	.
P3a latency	middle	middle	early	.	early	*late*
	c3/c2	c2/d2	c2/d3	c2/c3	d3/c2	d2/c2
Hypothesis: large and early						
MMN latency	late	*early*	*early*	late	.	.
MMN amplitude	small	middle	*large*	small	.	.
P3a latency	late	middle	middle	late	*early*	*early*

Note: comparison of hypotheses against obtained results in all ERP parameters that demonstrated statistically significant differences between contrasts. Results that are in line with the hypotheses are in italics.

MMN responses, but they did elicit early P3a responses peaking around 210–220 ms. By visual inspection of Figures 3 and 4, small MMN-like responses are still visible also to distorted chords among nondistorted chords. Also, when responses to deviant chords are inspected against the standard chords of the same paradigm, instead of the same chords acting as standards in another paradigm, negative MMN-like enhancements are seen in response to all d/c contrasts (see Figure 5). It is notable that nondistorted chords are highly familiar to Western individuals, while distortion in music may be more selectively familiar to only certain individuals. While a nondistorted chord in a distorted context introduces a familiar event, a distorted chord among nondistorted chords is likely to be a more novel, unfamiliar event in the course of the study. Novel auditory events elicit a so-called novelty-P3a (for a discussion on P3a vs. novelty-P3a, see Simons, Graham, Miles, & Chen, 2001). This may be the case also in the present study. When a novel sound is presented, N1 amplitude is enhanced and a large P3a follows (Escera, Alho, Winkler, & Näätänen, 1998). This N1-enhancement is, however, likely to be subtracted out in the present study where the responses to deviant chords were always compared to the responses to the same chords acting as standards (and thus visible only when responses to deviants are compared against a different stimulus acting as the standard, as seen in Figure 5).

When distorted chords were presented in a distorted context, the results were mixed and responses were small and late. Distorted triads among distorted dyads showed a statistically significant MMN and no P3a response, while the opposite was true for distorted dyads among distorted triads. (By visual inspection of Figures 3 and 5, small MMN-like responses are visible also for distorted dyads among distorted triads in the musicians.) On the contrary, nondistorted chords among nondistorted chords demonstrated a symmetrical pattern, although the obtained responses were similarly small and late as in the distorted/distorted contrasts. What could explain this asymmetry in contrasts where all chords are distorted? According to our original hypothesis, a power chord resembles a triad chord because of its acoustic structure (Lilja, 2009). When the level of distortion stays constant in the paradigm; that is, when all chords are distorted, the power chord vs. distorted triad chord contrast does not seem to elicit a consistent MMN-P3a pattern seen in the contrasts with nondistorted chords in a distorted or nondistorted context, nor a consistent no-MMN-P3a pattern seen in the contrasts with distorted chords in a nondistorted context. While this may be interpreted as evidence for a special role for the distorted dyad (i.e., power chord) in central auditory processing, it may also reflect general challenges in processing of unfamiliar and harmonically complex auditory material.

Larger P3a amplitudes in musicians than nonmusicians to music stimuli are in line with our hypothesis and with previous literature (Brattico et al., 2013; Trainor et al., 1999). However, the MMN amplitudes or the MMN or P3a latencies did not demonstrate this group difference. (With a p value of .11, group effect was only tentative for MMN amplitude, and the musician group demonstrated more negative mean amplitudes on FCz than the nonmusician group to all but distorted triads among distorted dyads that had very small values in general.) Furthermore, it is possible that the P3a enhancement in musicians is a result of their greater interest towards the presented stimuli. Such interest could be either conscious, attentive listening of the

sounds or very low-level, pre-conscious, automatic shifting of attention towards the sounds. Even though the participants were advised not to pay attention to the sounds that they heard, this was not controlled for (e.g., no questions were asked about the content of the movie they chose to watch). In fact, many musician participants spontaneously commented on the stimuli after the experiment, indicating that the stimuli had caught their attention. Musicians being more interested in music stimuli than nonmusicians is likely to be a general source of error in studies on cognitive neuroscience of music, leading to, for example, pronounced response amplitudes in musicians due to attention effects on top of the possible expertise effects. Thus, the present results cannot confirm a strong effect of music expertise on the studied phenomena. In line with previous research, music stimuli elicited larger MMN responses in the right than in the left hemisphere (Tervaniemi & Hugdahl, 2003; Zatorre, Belin, & Penhune, 2002). The lateralization pattern did not demonstrate differences between musicians and nonmusicians, evident in some earlier studies (Bever & Chiarello, 1974; Johnson, 1977; Kallman & Corballis, 1975; Messerli, Pegna, & Sordet, 1995; Peretz & Morais, 1979; Tervaniemi et al., 2011; Vuust et al., 2005).

In the present study, the nonmusicians outperformed the musicians in some cognitive subtests measuring linguistic skills (verbal long-term memory and verbal reasoning). This may be considered surprising, as music training is in many studies associated with enhanced cognitive skills (e.g., Corrigall, Schellenberg, & Misura, 2013; Schellenberg, 2004) and even verbal memory in particular (word list learning; Chan, Ho, & Cheung, 1998). It is, however, notable that in the present study, both groups consisted of educated adults with above-population-mean performance in linguistic tasks. The musician group consisted of either professional musicians (with a degree in music) or music students, while the nonmusicians were students of or had graduated from more literary study fields, for example humanities or social sciences. Thus, the obtained group differences should not be treated as evidence of music training resulting in lower linguistic abilities. Rather, they highlight that the slightly enhanced auditory cortical processing of chords seen in musicians is not explained or accompanied by a general cognitive enhancement in, e.g., auditory working memory or verbal skills, especially when compared to a group of literarily-oriented individuals. It is also notable that the participants in the present study were not questioned about their foreign language proficiencies, the only language criterion being that they were native Finnish speakers. This is likely to add variance in the ERP data.

While the present study demonstrated less pronounced effects of musicianship than seen in many prior studies, it is notable that half of the presented stimuli were distorted chords. It may be that distortion is not a very familiar auditory event even for the musician participants, except for listeners and players of heavy rock and related music genres. Thus, the choice of music genre among the musicians and also the nonmusician music listeners is likely to affect the neural processing of distortion. This is also likely to cause variance within the musician and nonmusician groups, thus making differences between the groups less pronounced. A more extensive questionnaire on genre preferences among participants and studying their associations with ERPs would offer interesting insights for neural plasticity of distortion processing (see also Istók, Brattico, Jacobsen, Ritter, & Tervaniemi, 2013).

During recent years, musical features specific to certain music genres have started to receive interest in music neuroscience. Also experts of certain music genres have been compared in brain studies. For example Vuust, Brattico, Seppänen, Näätänen, and Tervaniemi (2012) recently showed that processing of pitch slides—typical in jazz but rare in other music genres—is enhanced in jazz musicians compared to classical musicians, rock musicians, and nonmusicians. Similarly, Tervaniemi and colleagues (2015) presented a variety of changes in a musical paradigm to classical, jazz, and rock musicians, and found genre-specific adaptations in their music processing. Guitar distortion is a genre-specific musical feature that is likely to show differential brain activity in individuals with different music backgrounds. In future studies, comparing heavy rock musicians to experts of other genres would certainly be beneficial for understanding genre-specific neural plasticity.

Some additional suggestions for future studies arise from the present findings. First, it was unfortunately not possible to conduct a behavioral study on chord detection to the participants because of time limitations (other EEG paradigms were presented prior to the paradigm reported in this study). Comparing the behavioral discrimination accuracy and ERPs elicited in an attentive listening condition with ignore-ERPs would have offered more information on, for example, the level of processing. Furthermore, the set-up of the control conditions has some limitations in the present study. An optimal control condition presents each deviant stimulus in a paradigm where no standard stimulus is established and individual stimuli are presented with approximately the same probability than in the oddball paradigm amongst stimuli that share the important acoustic features with it (Schröger & Wolff, 1998;

Jacobsen & Schröger, 2001). However, since the ERPs to each stimulus are still compared against ERPs to the same stimulus (as standard) in the present study, most of the refractoriness should be omitted. Also, in the present paradigms, chords were presented as a continuous stream without silent gaps between stimuli. It is likely that this has affected the ERP waveforms, and a longer presentation rate might have elicited differential, for example more pronounced, change-related responses.

Taken together, the results obtained offer novel information on the cortical basis of harmonic distortion in Western listeners. While distortion has been used in heavy rock and related genres already for decades, it has by far received little if any interest in music neuroscience. Changes in the level of distortion compared to changes in the harmony of chords evoked earlier and larger brain responses in Western listeners. Also, simultaneous changes in distortion and harmony seemed to demonstrate so-called full additivity of MMN amplitudes: the amplitude size in response to double deviants was the sum of the amplitude sizes to single-deviants. Based on these findings, the present study suggests mostly independent cortical auditory processing of distortion and harmony in Western individuals. This is an intriguing finding from the viewpoint of psychoacoustics, since distortion is a strongly harmony-related acoustic phenomenon, which in previous studies (Lilja, 2009; Rossing et al., 2002) has been shown to generate new harmonic components to any type of chords and intervals. Furthermore, it suggests somewhat facilitated processing of distortion among Western musicians compared to nonmusicians. Since the musicians mostly had classical training, it is presumable that the effect was more related to general enhancements of auditory or music sound processing than due to musicians' particular experience with distortion.

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