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RESEARCH ARTICLE

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Pitch discrimination accuracy in musicians vs nonmusicians: an event-related potential and behavioral study

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Abstract Previously, professional violin players were found to automatically discriminate tiny pitch changes, not discriminable by nonmusicians. The present study addressed the pitch processing accuracy in musicians with expertise in playing a wide selection of instruments (e.g., piano; wind and string instruments). Of specific interest was whether also musicians with such divergent backgrounds have facilitated accuracy in automatic and/or attentive levels of auditory processing. Thirteen professional musicians and 13 nonmusicians were presented with frequent standard sounds and rare deviant sounds (0.8, 2, or 4% higher in frequency). Auditory event-related potentials evoked by these sounds were recorded while first the subjects read a self-chosen book and second they indicated behaviorally the detection of sounds with deviant frequency. Musicians detected the pitch changes faster and more accurately than nonmusicians. The N2b and P3 responses recorded during attentive listening had larger amplitude in musicians than in nonmusicians. Interestingly, the superiority in pitch discrimination accuracy in musicians over nonmusicians was observed not only with the 0.8% but also with the 2% frequency changes. Moreover, also nonmusicians detected quite reliably the smallest pitch changes of 0.8%. However, the mismatch negativity (MMN) and P3a recorded during a reading condition did not differentiate musicians and nonmusicians. These results suggest that musical expertise may exert its effects merely at attentive levels of processing and not necessarily already at the preattentive levels.

Keywords Pitch discrimination · Complex sounds · Musical expertise · Auditory event-related potentials · Mismatch negativity (MMN) · P3a · N2b · P3

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Introduction

The human brain has an amazing ability to adapt to environmental requirements on a short and on a long time scale. On a short scale, the brain represents the essential features of the surrounding environment and adjusts behavior according to the regularities and irregularities detected (e.g., Näätänen and Winkler 1999; Näätänen et al. 2001). On a longer scale, extensive use of one brain area or function may modulate brain functions permanently. In the case of peripheral or central loss of neurons, the neural functions are modulated within the same or another modality to compensate the deteriorated perceptual mechanisms (Rauschecker 1999; Kujala et al. 2001). Research on music perception in general and on musicians with high-level expertise in both music perception and performance in particular provides us with an excellent opportunity to probe these adaptive brain mechanisms in the healthy brain (Pantev et al. 2001; Pascual-Leone 2001; Rauschecker 2001; Schlaug and Chen 2001; Münte et al. 2002).

In addition to findings obtained while the subjects were performing a sound-related task during the experiment (e.g., Besson et al. 1994, Besson and Faïta 1995), the superiority of musicians in spectrally and/or temporally complex music-sound encoding has been observed while the subjects do not actively listen to the sounds (for a review, see Tervaniemi 2001). These studies on automatic neural encoding of musical material employed the mismatch negativity (MMN) component of the event-related potentials (ERPs). The MMN is evoked by an infrequently presented auditory stimulus (“deviant”) differing from the frequently occurring stimulus ("standard") in one or several physical or abstract parameters (Näätänen and Winkler 1999). It reflects the discrepancy between the neural code formed by the standard sound and that of the deviant infrequent sound. The MMN can be recorded even when the subject is performing a task unrelated to the stimulation under interest such as reading a book or playing a computer game (Alho et al. 1992). Sometimes, the MMN is followed by a frontocentrally distributed positive deflection, the P3a, indicating an involuntary attention switch towards the deviancy (for a review, see Escera et al. 2000). When the subjects are attending to the sounds, the MMN is followed by the N2b and P3 waves, reflecting conscious sound discrimination and target detection (Ritter et al. 1992; Näätänen et al. 1982, Näätänen 1992).

In a MMN paradigm, Brattico et al. (2001) compared musicians' vs nonmusicians' accuracy in processing pitch changes of identical magnitude in temporally complex auditory context (Western vs non-Western scales) and in single sounds. During the MMN recordings, the subjects concentrated on watching a silent movie with subtitles. In general, the pitch change in the Western condition evoked larger MMN amplitude than the change in the non-Western condition and, correspondingly, larger MMN in the non-Western condition than in the single-tone condition. This suggests that pitch change processing is facilitated in a complex sound context with familiar frequency ratios (Western condition) between subsequent tones when compared to unfamiliar frequency ratios (non-Western condition) or to single tones. Most importantly, the MMN latency was shorter in all conditions in musicians than in nonmusicians, implying that in musicians auditory change detection is faster than in nonmusicians.

Moreover, Koelsch et al. (1999) used the MMN to determine the preattentive pitch discrimination accuracy of violin players with ERPs and behavioral investigations. In their study, the standard stimulus consisted of major chords consisting of three sinusoidal tones with a perfect major third and fifth. The deviant stimulus was the same chord as the standard stimulus, except that the middle tone of the chord was marginally mistuned (<1%). This stimulation was presented to subjects while they were reading a book and while they were asked to detect the deviant chords. During a reading task, the deviants elicited the MMN only in musicians. In the behavioral task, nonmusicians only detected 10% of the deviant chords, whereas violin players detected 80%. In the discrimination condition, a significant MMN was followed by N2b and P3b deflections in musicians. Nonmusicians had a small MMN without subsequently elicited N2b or P3. These results demonstrate that highly trained violin players to whom pitch discrimination is of crucial importance automatically detect pitch differences which are undetectable for nonmusicians.

The present study further compared the pitch processing accuracy in musicians vs nonmusicians. Of specific interest were the effects of parametric manipulations in the magnitudes of pitch deviance and also in the subjects' attentional focus. To determine the specificity of pitch discrimination accuracy of musicians, all of whom were at professional level but with experience with a variety of instruments (e.g., guitar, piano, wind and string instruments), we utilized small pitch differences close to threshold as there is evidence that musicians have smaller, just noticeable differences in pitch perception than nonmusicians (Fastl, personal communication, based on data reported by Fastl and Hesse 1984). However, also larger pitch differences were employed in order to determine whether and how the musicians' superiority is reflected in behavioral and ERP measures at suprathreshold levels.

Materials and methods

Behavioral experiment

This behavioral experiment was implemented prior to the ERP experiment in order to establish a valid and reliable frequency difference threshold.

Spectrally complex tones, each consisting of their fundamental frequency and the four smallest equiloud overtones were employed. The sounds had their natural harmonics since previously both behavioral and neural pitch discrimination were found to be more sensitive when sounds are spectrally rich than when they consist of one (fundamental) frequency only (Tervaniemi et al. 2000a, 2000b).

The stimuli were synthesized by a Soundblaster 16-bit sound card using the Goldwave software. All sounds had a presentation time of 300 ms including 5 ms rise and 5 ms fall times and were presented binaurally via headphones (Sennheiser HD 435) at an intensity of 60 dB sound pressure level (SPL) with ERTS software (Berisoft, Frankfurt, Germany).

The stimuli were presented in pairs of two successive tones with a silent interstimulus interval (ISI) of 1400 ms duration, so the presentation of a pair always lasted 2 s. The response time was unlimited. One tone of each pair constantly possessed a frequency of 528 Hz (c^5on the Western scale) and was presented randomly on first or second position. The 30 comparative tones possessed frequencies between 529 and 558 Hz in 1-Hz steps. The frequency difference threshold was determined in the two alternative-forced choice (2AFC) procedure in which subjects had to decide whether the first or second tone of the pair was higher in pitch. This paradigm was applied in an adaptive way, realized by the weighted up-down method (Kaernbach 1991) with a probability of 0.75 for the correctness of each individual just noticeable difference (jnd). The interval 528–559 Hz that had to be compared first was decreased by 1 Hz following each correct answer and increased by 3 Hz after each false answer.

Twelve healthy and normal hearing subjects aged between 20 and 40 years (mean age: 26), six males and six females, participated in this threshold measurement. Nine participants had amateur musical experience while the others were without personal experience in playing an instrument or singing. They were seated comfortably in an acoustically shielded cabin and gave answers immediately after each comparison by pressing a button on a keyboard.

The mean frequency difference threshold of the 12 subjects was 0.73% (3.8 Hz higher in pitch than the constant 528-Hz tone). Consequently, this pitch deviation was chosen to represent a minimum threshold that might differentiate musical experts and nonmusicians in their fine-grained pitch discrimination.

ERP study

Subjects

Two groups of 13 healthy, normal hearing, and right-handed subjects each participated in this experiment. None of them had participated in the behavioral study. The participants were paid for their participation in the experiment and gave their informed consent after the details of the procedure had been explained to them.

The musical experts were between 23 and 35 years (mean: 27.7 years, nine males). All of them were professional musicians who were playing a large variety of instruments (e.g., guitar, piano, wind and string instruments; see Table 1). They had started training in music at the age between 3 and 14 years and were currently playing for at least 20 h/week. The group of nonmusicians consisted of subjects aged between 19 and 28 years (mean age: 21.9 years, four males). Eight of them have never had lessons in a musical instrument or in singing nor had sung in a choir, one subject was a member of the school choir during fifth and sixth class, and four subjects had just received musical training for 3 months maximum in their first–third class.

Stimulation and procedure

From the frequencies tested in the behavioral experiment (see above), four were selected for the ERP recordings. The lowest frequency, used as the standard frequency, was 528 Hz. The deviant frequencies were 532 Hz (0.76%, at the frequency difference threshold), 539 Hz (2.1%, about a quarter tone higher than the standard), and 550 Hz (4.2%, about semitone higher than the standard). As in the behavioral experiment, also the sounds used in ERP recordings consisted of their fundamental frequency and the four smallest equiloud overtones. They were 300 ms in duration (including 5 ms rise and 5 ms fall times). The ISI was 300 ms; stimulus onset (SOA) was thus 600 ms. The stimuli were presented binaurally via headphones at an intensity of 60 dB SPL.

The experiment was conducted in an acoustically and electrically shielded cabin. Oddball paradigm was used in two conditions. In the *unattend* condition, the subjects were instructed to read a self-selected book and to ignore the repetitive sounds. Thereafter, they were asked whether they had noticed and could describe any peculiarity concerning the sequence of the acoustical stimuli. In the *attend* condition, the subjects were informed that irregularly a few sounds varying in pitch would occur. They were asked to focus their attention on the sounds and to immediately press a button after detecting a sound differing in frequency. To avoid any carryover effects of attention (e.g., see Näätänen et al. 1993), the unattend condition always preceded the attend condition.

The total number of stimuli was 2800 in the unattend condition and 1400 in the attend condition. In addition, five standard tones were presented in the beginning of each block in order to avoid starting a block with a deviant. Each deviant occurred with a probability of 0.05 in a pseudo-random manner to prevent two deviants to appear successively. Accordingly, 140 deviants in the unattend condition and 70 deviants in the attend condition were presented. The use of an unequal number of deviants

Table 1 The musical background of the musicians

First instrument	Age when started to play	Secondary instruments	Weekly hours in practicing	Still engaged in playing the first instrument	Present major instrument
Piano	5	Oboe, cello	25	Yes	Oboe
Recorder	6	Singing, piano, organ, flute	25	No	Singing/piano
Violin	7	Viola	35	No	Viola
Recorder	9	Violin, piano	30	No	Violin
Recorder	8	Piano, organ, trombone	35	No	Piano/organ
Violin	3	Piano	35	Yes	Violin
Piano	6	Horn	35	Yes	Piano
Recorder	8	Flute, Guitar, Piano	30	Yes	Flute
Recorder	6	Piano, organ, violin	20	No	Piano/organ
Recorder	7	Clarinet, guitar, piano	21	Yes	Clarinet
Violin	7	Piano, bass guitar, singing	20–30	Yes	Violin
Singing	14	Piano	30	Yes	Piano
Violin	7	Viola, piano, harpsichord	28	Yes	Viola

in the attend and unattend conditions is justified by the previous data according to which the ERPs display a better S/N ratio when the subjects are attending to the sounds than when they are ignoring the sounds (e.g., due to a smaller amount of muscle artifacts).

Data recording and analysis

EEG was continuously recorded by Ag-AgCl electrodes attached to the scalp at ten positions: on the midline at FZ, CZ, PZ and OZ, on the left hemisphere at F3 and FC5, on the right hemisphere at F4 and FC6 according to the extended 10–20 system (American Electroencephalographic Society, 1991), and at both mastoids (ML and MR). The reference electrode was attached to the tip of the nose. Horizontal electrooculogram (EOG) was recorded by electrodes applied at the left and right outer canthi and vertical EOG by electrodes placed above and below the left eye. Electrode impedances were kept below 5 kohms. EEG was filtered and digitized online with a band pass of 0.05–40 Hz and a sampling rate of 200 Hz. SynAmps amplifiers (NeuroScan Inc., Herndon, Va., USA) were used.

Since all the ERP components under interest occurred at frequencies below 15 Hz, the continuous EEG records were filtered offline with a band pass of 1–20 Hz and divided into epochs of 600 ms duration including a 100 ms prestimulus baseline (EEProbe 3.2 Software by ANT). To eliminate activity caused by extracerebral sources, epochs with a signal change exceeding 100 μV on any recording channel were excluded from the analysis. Also, all standard tones following a deviant were discarded from analysis. Subsequently, the remaining epochs were averaged time-locked to stimulus onset separately for each stimulus type and both conditions of the experiment. For visualization, grand averages were derived for all participants as well as for both groups.

Behavioral data during the attend condition were recorded and analyzed at an individual level in terms of hit rate, false alarms, and response time. Only reactions given within between 150 and 1200 ms after the target stimulus onset were accepted.

The ERP effects were quantified using mean ERP amplitudes in 40-ms time windows centered on the peak of the respective component in the grand average ERP difference waves. ERP amplitudes were averaged for separate regions of interest (ROI) for each component. The ROIs and the parameters of the windows are shown in Table 2 for each condition and deviant. In order to quantify the full MMN amplitude, the ERP was rereferenced against the average of the mastoids in unattend and attend conditions (Schröger 1998; Sinkkonen and Tervaniemi 2000). The other ERP components were quantified by using the nose-referenced data.

Statistical analyses

By two-way analyses of variance (ANOVA) with the factors deviancy (levels: small, medium, and large deviant) and group (levels: musicians vs nonmusicians), the main effects of the magnitude of pitch deviance, and musical expertise, as well as their interaction was tested in both unattend and attend conditions (SPSS software) for the MMN, P3a, and N2b amplitudes. The latencies of these components were not analyzed since visual inspection suggested that the latencies do not remarkably differ between the groups (see Fig. 2, Fig. 4). Correspondingly, hit rate, false alarm rate, and reaction times were analyzed. Additionally, a three-way ANOVA was used to determine main effects of the magnitude of pitch deviance, musical expertise, P3 topography (levels: Fz, Pz), as well as their interactions. Post hoc tests were conducted by *t*-tests (two-tailed). Greenhouse-Geisser corrections were employed when applicable.

Results

Unattend condition

MMN

As Fig. 1 and Fig. 2 illustrate, the MMN was elicited in both subject groups by all three deviants as reflected by the negativity in frontal areas and by a distinct positive

Table 2 Time windows and regions of interest (ROIs) for ERP quantification separately for each condition and deviant type

Condition	Deviant	MMN (ms) (FZ, F3, F4, FC5, FC6, CZ)	N2b (ms) (FC5, FC6, CZ)	P3a (ms) (FZ, F3, F4, FC5, FC6, CZ)	P3 (ms) (FZ, PZ)
Unattend	Small	185–225		285–325	
	Medium	160–200		275–315	
	Large	155–195		260–300	
Attend	Small	165–205	235–275		360–400
	Medium	145–185	210–250		335–375
	Large	135–175	195–235		325–365

deflection at both mastoids. The MMN peaked between 175 and 205 ms depending on the magnitude of the deviance.

Across both groups, the MMN amplitude increased as a function of increasing deviance (main effect deviance: $F_{(2,48)}$=61.9, P<0.001). Post hoc tests revealed that the larger the deviance, the larger the MMN amplitude (P<0.01 in all comparisons) (Fig. 1, Table 3). In a group-wise comparison, the MMN amplitude did not differ between musicians and nonmusicians across the three conditions, neither was there an interaction between the magnitude of the deviance and subject group (Fig. 2, Table 3).

P3a

The MMN was followed by a P3a, which peaked between 280 and 305 ms. Across both groups, the P3a evoked by the three deviants significantly differed in amplitude from each other (main effect deviance: $F_{(2,48)}$=9.3, P<0.001). The post hoc comparisons indicate that the P3a amplitude was smaller after the small deviant than after the medium or large deviant tones (small vs medium deviant: P<0.01; small vs large deviant: P<0.001; medium vs large deviant: n.s.) (Fig. 1, Table 3).

In a group-wise comparison, the P3a amplitude did not differ between musicians and nonmusicians across the three conditions, neither was there an interaction between the magnitude of the deviance and subject group (Fig. 2, Table 3).

Attend condition

MMN

Also in the attend condition, the MMN (with a parallel positivity in mastoids) was observed. It peaked between 155 and 185 ms (Fig 3, Fig. 4). Across both groups, the MMN amplitude increased as a function of increasing deviance (main effect deviance: $F_{(2,48)}$=41.7, P<0.001). Paired post hoc tests between small, medium, and large deviants confirmed that the magnitude of the deviance was directly reflected in the MMN amplitude (P<0.001 in all comparisons) (Fig. 3, Table 3). In a group-wise comparison, the MMN amplitude did not differ between the groups. Interaction between the magnitude of deviance and group remained nonsignificant (Fig. 4, Table 3).

N2b

As Fig. 3 and Fig. 4 illustrate, the MMN was followed by the N2b peaking between 215 and 255 ms. Across-group comparison indicated that the larger the deviance, the larger the N2b (main effect deviance: $F_{(2,48)}$=15.4, P<0.001). According to the post hoc comparisons, the N2b amplitude was smaller after the small deviant than

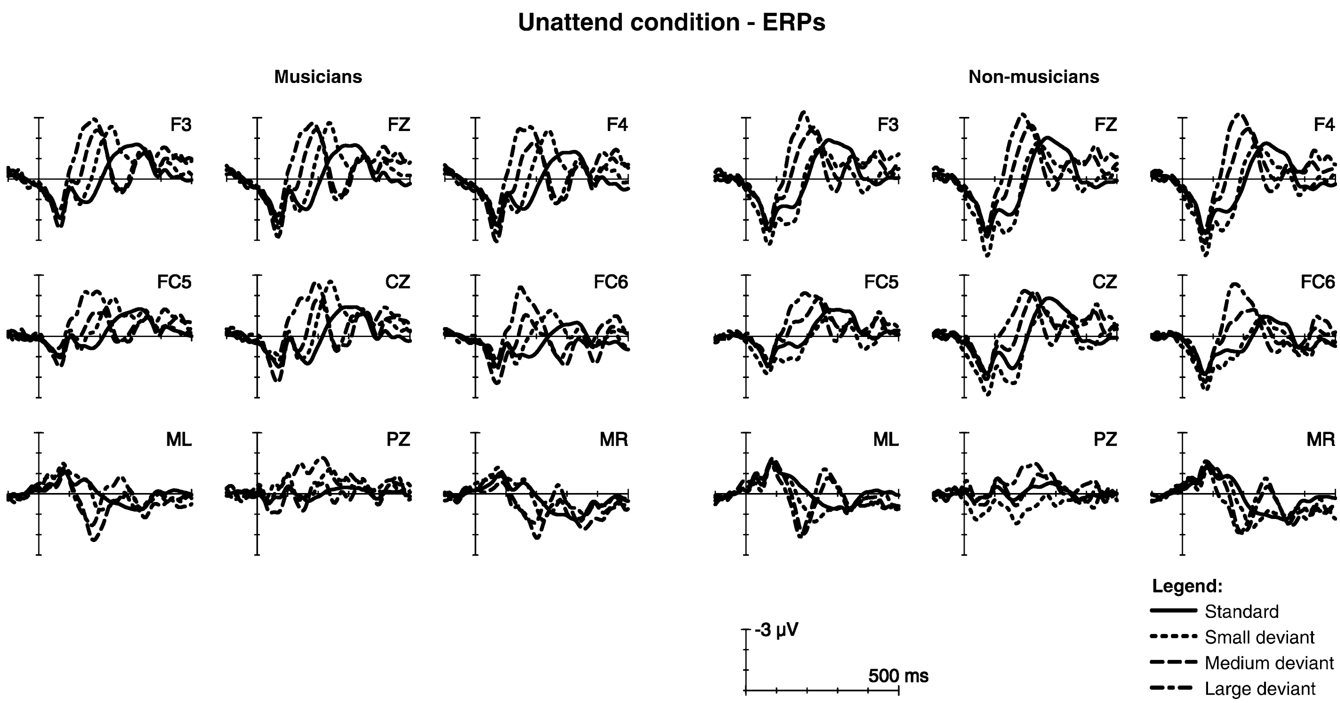

Fig. 1 The grand-average ERPs elicited by standard tone (continuous line) and deviant tones (dashed and dotted lines) in musicians (left) and non-musicians (right). The deviant tones differed from the standard tone in frequency so that the small deviant was 0.8%, medium 2%, and large 4% higher in frequency than the standard tone (528 Hz). These ERPs were recorded while the subjects read a book of their own choice and paid no attention to the sounds. The x-axis denotes time in milliseconds (onset of the sounds at 0 ms) and the y-axis the strength of the ERPs in microvolts.

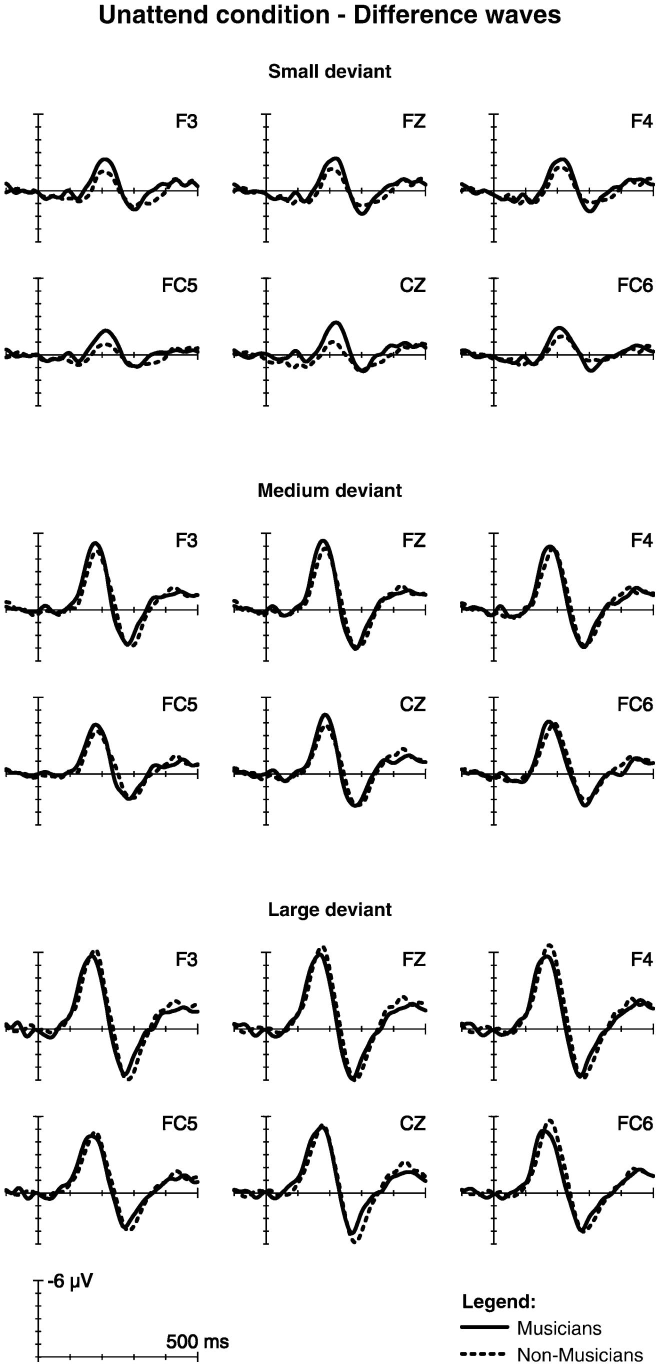

Fig. 2 The subtraction curves (deviant minus standard tone ERPs) in musicians (continuous line) and non-musicians (dotted line). These data were referenced to the average of the mastoid values (see “Methods”).

after the medium or large deviant tones (small vs medium deviant $P<0.01$; small vs large deviant $P<0.001$; medium vs large deviant n.s.) (Fig. 3, Table 3).

In group-wise comparisons, the N2b amplitude was larger in musicians than nonmusicians (main effect group: $F_{(1,24)}=5.4$, $P<0.05$) (Fig. 4, Table 3). The group × deviance interaction was not significant.

P3

The N2b was followed by P3. Across both groups, the P3 amplitude increased as a function of increasing deviance (main effect deviance: $F_{(2,48)}=35.3$, $P<0.001$). Paired post hoc tests between small, medium, and large deviants confirmed that the magnitude of the deviance was directly reflected in the P3 amplitude ($P<0.01$ in all comparisons) (Fig. 3, Table 3). Pooled across the Cz and Pz electrodes, the P3 amplitude was larger in musicians than in nonmusicians (main effect group: $F_{(1,24)}=5.5$, $P<0.05$) (Fig. 4, Table 3).

Additional analysis, taking into account also the distribution of the P3, indicated that its amplitude was larger at Pz than at Fz (main effect parietality: $F_{(2,48)}=39.1$, $P<0.001$). Moreover, the smaller deviants evoked the P3 with more frontal distribution than the larger deviants (interaction between deviancy and parietality: $F_{(2,48)}=5.5$, $P<0.05$). There were no other significant main effects or interactions.

Behavioral data of the attend condition

Hit rate

Across both groups, the hit rate became more accurate as a function of increased magnitude of the deviance ($F_{(2,48)}=71.2$, $P<0.001$). Paired post hoc tests between hit rates for small, medium, and large deviants confirmed that the hit rate directly reflected the magnitude of the deviance ($P<0.001$ in all comparisons) (Table 4). In addition, a group × deviance interaction was observed ($F_{(2,48)}=37.8$, $P<0.001$).

In group-wise comparisons, musicians were more accurate than nonmusicians in detecting the pitch changes ($F_{(1,24)}=33.7$, $P<0.001$). This resulted from the musicians being more accurate than nonmusicians in detecting small and medium deviants ($P<0.01$ and $P<0.05$, respectively) (Table 4). In contrast, due to ceiling effects, hit rates of the large deviant did not differ between the groups.

Reaction time

Across both groups it was observed that the larger the deviance, the faster the reaction time ($F_{(2,48)}=196.8$, $P<0.001$). Paired post hoc tests between small, medium, and large deviants confirmed that the magnitude of the deviance was directly reflected in the reaction time ($P<0.001$ in all comparisons) (Table 4).

In group-wise comparisons, musicians were faster than nonmusicians in detecting the pitch changes ($F_{(1,24)}=7.7$, $P<0.05$). The group × deviance interaction was not significant.

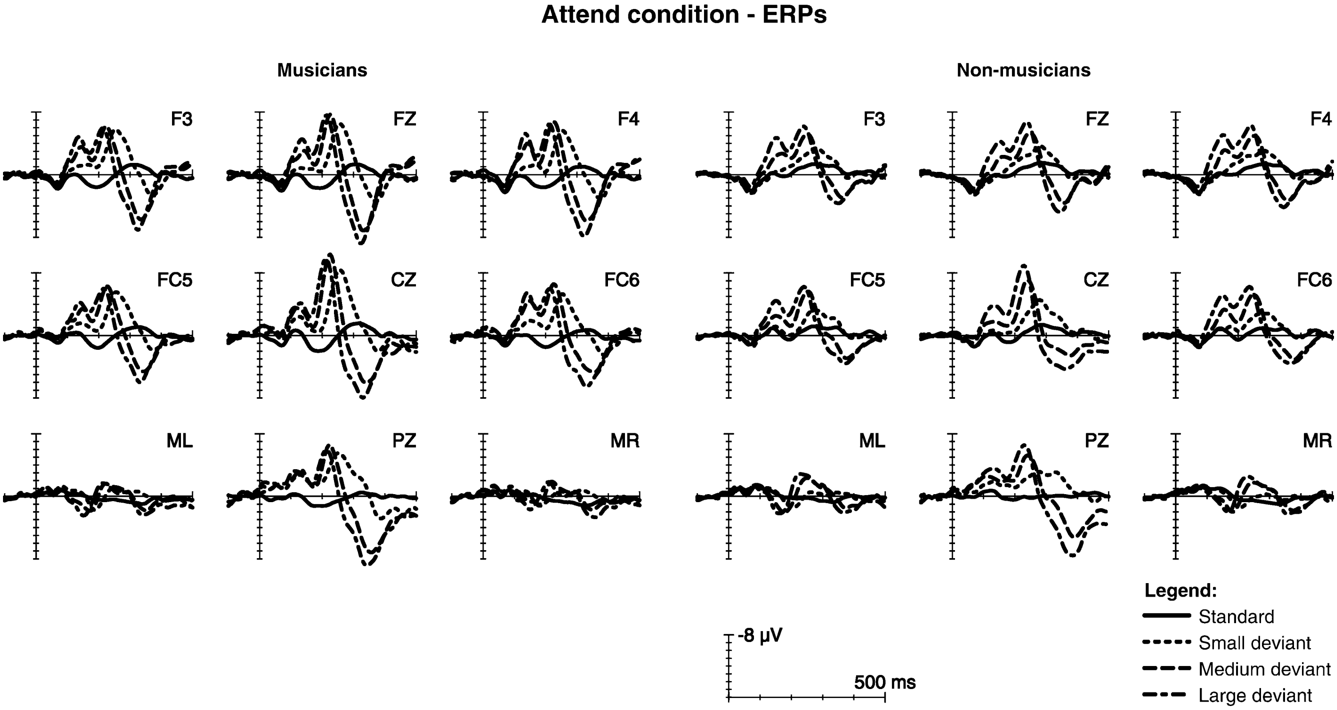

Fig. 3 The grand-average ERPs elicited by standard tone (continuous line) and deviant tones (dashed and dotted lines). These ERPs were recorded while the subjects performed a target-detection task.

Table 3 The mean amplitudes of the MMN, P3a, P2b, and P3 amplitudes (SEM in parentheses). The values depict the average amplitude across the ROI used (see Table 2)

		MMN		N2b	
Condition	Deviant	Nonmusicians	Musicians	Nonmusicians	Musicians
Unattend	Small	−1.3 (0.4)	−2.1 (0.5)		
	Medium	−3.8 (0.4)	−4.3 (0.6)		
	Large	−5.4 (0.4)	−4.9 (0.4)		
Attend	Small	−1.7 (0.3)	−3.3 (0.5)	−2.0 (0.5)	−5.9 (1.1)
	Medium	−4.1 (0.5)	−4.8 (0.7)	−4.4 (1.0)	−7.6 (1.2)
	Large	−6.1 (0.6)	−6.2 (1.0)	−5.8 (1.1)	−7.7 (0.9)
		P3a		P3	
Condition	Deviant	Nonmusicians	Musicians	Nonmusicians	Musicians
Unattend	Small	0.8 (0.3)	0.6 (0.2)		
	Medium	1.2 (0.4)	1.7 (0.3)		
	Large	1.8 (0.3)	1.7 (0.3)		
Attend	Small			−0.2 (0.5)	2.7 (0.9)
	Medium			3.7 (1.0)	6.7 (1.0)
	Large			5.4 (1.1)	8.2 (1.3)

Table 4 The response times and hit rates (SEM in parentheses)

	Response time (ms)		Hit rate (%)	
Deviant	Nonmusicians	Musicians	Nonmusicians	Musicians
Small	501 (25)	430 (14)	41.7 (7.4)	91.3 (2.9)
Medium	404 (19)	337 (8)	94.1 (2.2)	100 (0)
Large	368 (19)	315 (8)	98.9 (0.6)	99.9 (0.1)

Discussion

The present study addressed the neurally and behaviorally indexed expertise of musicians in pitch discrimination. By now, the neural determinants of musical expertise have been investigated by several paradigms in modern cognitive neuroscience. As summarized in the "Introduction," brain responses such as N1, MMN, P3, and late positive component (LPC) were enhanced in musicians when compared with nonmusicians (N1: Pantev et al. 1998, 2001; Shahin et al. 2003; MMN: Koelsch et al. 1999; Brattico et al. 2001; Tervaniemi et al. 2001; van Zuijen et al. 2004; P3: Trainor et al. 1999; Crummer et al. 1994; LPC: Besson et al. 1994, Besson and Faïta 1995). The most relevant finding in the present context was provided by Koelsch et al. (1999) who showed that professional violin players neurally and behaviorally discriminated tiny

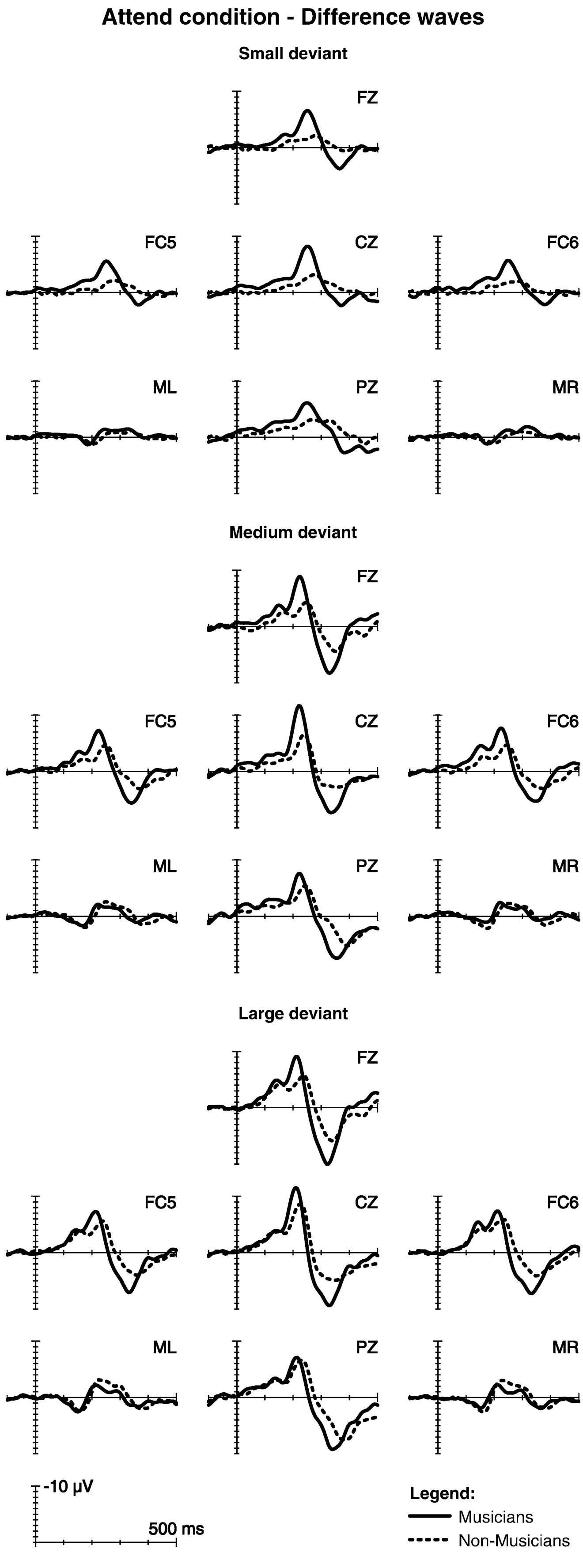

Fig. 4 The subtraction curves (deviant minus standard tone ERPs) in musicians (continuous line) and non-musicians (dotted line).

pitch changes, which could not be detected by nonmusicians. Our specific interest was to determine whether musicians with a diverse musical background have facilitated accuracy in detecting pitch changes at automatic and/or attentive levels of sound processing.

The present data indicate that when compared with nonmusicians, musicians were faster to behaviorally discriminate the pitch changes irrespectively of the size of the pitch shift. Moreover, the musicians were more accurate in this task with the small and medium pitch shifts (0.8, 2%) (Table 4). Comparably, the N2b and P3 components recorded during this behavioral task were enhanced in amplitude in musicians when compared with nonmusicians with all the deviants employed (Fig. 3, Fig. 4). However, the ERPs recorded while the subjects concentrated on reading and not listening to the repetitive sound stimulation displayed a different data pattern: MMN or P3a did not differentiate the subject groups (Fig. 1, Fig. 2).

The present finding carries several important implications. First, although musicians were faster and more accurate in the behavioral task than nonmusicians, also nonmusicians detected the pitch changes quite reliably. This behavioral result thus seems to be discrepant from observations by Koelsch et al. (1999). Their nonmusicians could not detect 1% mistuning of middle tone of the chord and, correspondingly, this mistuning did not evoke a MMN in them. This discrepancy is presumably due to the differences in stimulation. While the present study used spectrally rich sounds with close to 1% pitch change in all its partials, Koelsch et al. used chords in which only the middle sound was 1% mistuned, this stimulation being optimized to probe pitch sensitivity of violinists. So, it may be that had smaller pitch changes also been used in the present study, a group difference in reading/ignore condition ERPs would have been present. In other words, the present result of musicians' superior pitch discrimination accuracy observed in attentive but not in ignore condition may partially reflect the easiness of the perceptual task. Second, during the reading task, the present stimulation paradigm allowed memory traces to be established with comparable accuracy in both subject groups. However, during attentive listening, the musicians were able to utilize the memory trace information more efficiently than the nonmusicians were. The present data thus corroborate with the views according to which the automatically formed and activated memory traces create a basis for subsequent attentive processes (see Schröger 1997 and Näätänen and Winkler 1999 for further theoretical considerations).

However, in parallel, our data suggest that even if the neurocognitive processing during these first stages does not differ as a function of subjective expertise, it may differ when more efficient attentional processing is involved in the given task. This might evidence that in experts the attentional processes can more efficiently utilize the preattentively encoded neural information.

Third, in the present study, three different magnitudes of pitch change among the spectrally rich sounds were used. In general, the larger the pitch change, the larger the MMN, P3a, N2b, and P3 amplitudes as well as the faster and more accurate the behavioral performance. These data correspond with the previous data obtained either in ignore condition (during a reading task, e.g., Sams et al. 1985; Tiitinen et al. 1994) or in attend condition as indexed by ERPs and behavioral data (e.g., Amenedo and Escera 2000; Berti and Schröger 2001; Novak et al. 1990, 1992a, 1992b; Ritter et al. 1979). At the same time the present data also expand the previous findings by obtaining all the evidence in a within-subject design.

Fourth, the present data introduce an interesting discrepancy between the introspective reports of the subject and their ERPs as obtained in the unattend condition. According to their verbal reports, the musicians were remarkably accurate in describing the number and magnitudes of the deviants while the nonmusicians were able to report the presence of "some different sounds." In addition to more advanced verbal strategies available for the musicians in describing the deviants, this might also imply that the involuntary attention of musicians had been switched towards the pitch changes more often than in nonmusicians. However, as suggested by the lack of the group difference in the P3a amplitude (Escera et al. 2000), this does not seem to be the case. It could be speculated that for musicians relatively short and few attentional elapses are sufficient to enable accurate encoding of the unattended acoustic environment even until the stage of the verbal encoding.

Thus, the present data imply that musicians are not superior in pitch discrimination in all circumstances. As discussed above, this might be caused by the easiness of the present pitch discrimination task. Alternatively, it cannot be ruled out that the lack of statistical group difference in the MMN amplitude (possibly present according to visual inspection with the smallest deviant; see Fig. 3 and Table 3) results from a relatively small MMN amplitude combined with a large within-group variation.

To summarize, the present data suggest that even though the ERPs recorded in ignore condition do not statistically differ between the subject groups, musicians still perform superior to nonmusicians during attentive pitch discrimination tasks. This implies that musical expertise may have facilitating effects selectively for cognitive processes under attentional control, at least with salient sound changes also perceptually discriminable by nonmusicians.

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