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New fast mismatch negativity paradigm for determining the neural prerequisites for musical ability

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ABSTRACT

Studies have consistently shown that the mismatch negativity (MMN) for different auditory features correlates with musical skills, and that this effect is more pronounced for stimuli integrated in complex musical contexts. Hence, the MMN can potentially be used for determining the development of auditory skills and musical expertise. MMN paradigms, however, are typically very long in duration, and far from sounding musical. Therefore, we developed a novel multi-feature MMN paradigm with 6 different deviant types integrated in a complex musical context of no more than 20 min in duration. We found significant MMNs for all 6 deviant types. Hence, this short objective measure can putatively be used as an index for auditory and musical development.

1. Introduction

Learning and performing music requires a variety of auditory skills, placing demands on the underlying neural substrates as well as on the brain's plastic potential. Recent studies of human brain function indicate that musicians are more sensitive to basic auditory features than non-musicians (Brattico et al., 2001; Koelsch et al., 1999; Pantev et al., 1998) and, further, that behavioral measures of auditory performance correlate with event-related potentials (ERPs) as recorded by electroencephalography (EEG) (Lang et al., 1990; Pakarinen et al., 2007; Schneider et al., 2002). Studies indicate that the stimuli need to consist of realistic, complex musical material in order to disclose fine-grained processing differences between participants (Brattico et al., 2001; Koelsch et al., 1999; Seppänen et al., 2007). Therefore, there is a need for paradigms integrating different auditory features into musically relevant contexts (Vuust et al., 2011) in order to

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study the development of auditory skills and musical expertise.

The mismatch negativity (MMN) (Näätänen et al., 1978) is a component of the auditory ERP recorded with EEG related to change in different sound features such as pitch, timbre, location of sound source, intensity and rhythm (Näätänen et al., 2001, 2007; Näätänen and Winkler, 1999). It peaks approximately 100–200 msec after change onset, with the amplitude and latency of the MMN depending on deviation magnitude such that larger deviations yield larger and faster MMNs (Näätänen et al., 1987).

Recording the MMN to musically relevant sound features in a musical context may be a possible objective way of measuring auditory skills for the following reasons: first, the MMN is automatically elicited, even in the absence of subjects' attention towards the stimuli, typically in paradigms where they are reading a book or watching a silent video while being exposed to sound patterns (Alho, 1992; Fujioka et al., 2004). Second, the amplitude and latency of the MMN is associated with auditory behavioral measures (Lang et al., 1990; Sams et al., 1985; Tiitinen et al., 1994). Such a correlation was recently extended by Seppänen et al. (2007) to include more musically related tests incorporating ear-training aspects. Third, the MMN is sensitive to discrimination learning (Näätänen et al., 1993) and musical expertise (Brattico et al., 2009; Nikjeh et al., 2009; Russeler et al., 2001; Vuust et al., 2005). In particular, specific auditory skills required for performing different musical tasks such as conducting an orchestra (Munte et al., 2001; Nager et al., 2003), playing certain instruments (Koelsch et al., 1999), or musical genres (Seppänen et al., 2007), lead to special sensitivity to different sound features reflected in the amplitude and latency of the MMN (for a review, see Tervaniemi, 2009).

Some disadvantages of the traditional MMN paradigms used are that they are time-consuming (often exceeding an hour) and they do not sound musical. However, Näätänen et al. recently introduced a novel paradigm (Näätänen et al., 2004) in which several types of acoustic changes are presented in the same sound sequence. This allows for several MMNs to be independently elicited for different auditory attributes, making the duration of the experiment significantly reduced to less than 15 min. Importantly, no difference was observed between the MMNs recorded using the new paradigm and the ones obtained in the traditional oddball paradigm.

Here we present a new, fast, musical multi-feature MMN paradigm, in which 6 types of acoustic changes relevant for musical processing in different musical genres are presented in the same sound sequence. Specifically, 5 of the 6 musical features are aspects of musical sound that previously have elicited larger MMNs according to musical expertise: pitch mistuning, intensity, timbre, sound-source location, and rhythm (Brattico et al., 2009; Pantev et al., 2003; Tervaniemi et al., 2006; Vuust et al., 2009). Since we wanted a paradigm that could be used to compare non-musicians to musicians, as well as musicians from different musical genres with each other, we included a pitch slide typical for improvisational music instead of classical music (see also Tervaniemi et al., 2006; Vuust et al., 2005).

In comparison with the recently developed multi-feature paradigm (Näätänen et al., 2004; Pakarinen et al., 2007), the present paradigm has a greater similarity to real music. It is based on a musical figure, well-known in many genres of Western tonal music: the Alberti bass, an accompaniment originally encountered in classical music such as Mozart's sonatas or Beethoven's rondos, and later adopted with variations in other contemporary musical genres (Fuller, 2010). Here we show that the musical multi-feature paradigm enables one to record MMNs corresponding to the respective MMNs obtained in the traditional one-deviant paradigms.

2. Methods

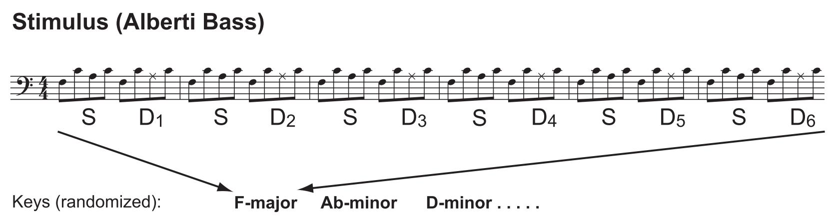
2.1. *Subjects*

Eleven subjects (mean age 26, range 22–27 years; 4 females) gave informed consent and participated in the experiment. The subjects had no formal music training apart from music lessons at primary and secondary school, and were never taught to play an instrument, with the exception of one subject who had played the piano for less than a year when he was 8 years old. All participants had normal hearing and reported no cognitive deficits or neurological diseases. The experiment protocols were done in accordance with the Declaration of Helsinki, and approved by the Ethical committee of the Department of Psychology, University of Helsinki. Subjects were paid for their voluntary participation.

2.2. *Stimuli and procedure*

Auditory stimuli were similar to the 'Optimal' paradigm presented in Näätänen et al. (2004), yet were more complex and musically enriched. In the Optimal paradigm, a 'standard' simple tone is presented once after each 'deviant' tone. In this way, it is possible to record ERP responses for many auditory feature deviations in a considerably shorter time, and with an equally good signal-to-noise ratio as the traditional oddball paradigms. Similarly, in the present study, standards and deviants were alternated, but each of them consisted of musical 4-tone patterns rather than single tones (Fig. 1).

The standard pattern consisted of either major or minor mode tones arranged in an 'Alberti bass' configuration, an accompaniment commonly used in the Western musical culture in both classical and improvisational music genres. To make the stimuli more musically interesting, we changed the key every 6th measure, allowing for 6 different types of deviants to appear exactly once in each key, in a randomized order. The order of the 24 possible keys (12 major and 12 minor) was pseudo-randomized, so that each key appeared once for every 24 transpositions. The keys were kept in the middle register of the piano with the bass note between F3 and E4. Sound stimuli were generated using the Wizoo Acoustic Piano sample sounds from the software sampler Halion in Cubase (Steinberg Media Technologies GmbH). Deviant patterns were similar to standards, except that the third tone of the pattern was modified with Adobe Audition (Adobe Systems Incorporated) as illustrated in Fig. 1. The pitch deviant was created by mistuning the third tone by 24 cents, tuned downwards in the major mode, upwards in the minor mode. The rhythm deviant was created by anticipating the



S:	Standard	
D_1:	Pitch-deviant:	24 cents lower
D_2:	Timbre-deviant:	filtered, having an 'old time radio' effect
D_3:	Location-deviant:	slightly shifted to the left
D_4:	Intensity-deviant:	6 dB reduction
D_5:	Slide-deviant:	sliding up from a whole note below
D_6:	Rhythm-deviant:	30 ms earlier

Fig. 1 – Stimulus. "Alberti bass" patterns alternating between standard sequence and a deviant sequence played with piano sounds. Patterns were periodically transposed to different keys and/or modality with an interval of 6 bars. Each tone was 200 msec in duration, with an SOA of 5 msec, yielding a tempo of approximately 146 beats/min. Comparisons were made between the third note of the standard sequence and the third note of the deviant sequence.

third note by 30 msec compared with when it was expected. The timbre used the 'old-time radio' effect provided with Adobe Audition. The location deviant was generated by decreasing the amplitude of the right channel up to 10 dB, perceptually resulting in a sound coming slightly from a location left centers (~70°). The loudness deviant was made by reducing the original intensity by 6 dB and the pitch-slide deviant by bending the pitch of two notes separated by two semitones. Sounds (the individual tones) were amplitude normalized. Each tone was in stereo, 44,100 in sample frequency, and 200 msec in duration, having an ISI of 5 msec.

A pilot ERP study was conducted to optimize the deviants by their salience, resulting in the parameter values used. Randomization was performed in MatLab and stimuli were presented with the Presentation software (Neurobehavioral Systems).

Auditory stimuli consisted of a 20-min block. Participants passively heard auditory sequences through headphones (Sony MDR-7506, sound pressure level 50 dB above individual threshold.). Their main task was to concentrate on a silenced document film while sitting on a comfortable chair in a shielded chamber. Before EEG recording, participants answered a background questionnaire consisting of questions about their musical knowledge. After the EEG recording, the Advanced Measure of Musical Audiation (AMMA) musicality test was conducted to obtain an additional behavioral measure of the musical skills of subjects (Gordon, 1989). The AMMA test has been standardized with over 5000 American students, with and without musical background. It lasts about 15 min and includes 30 pairs of short melodies, 10 with a change in pitch (AMMA total score), 10 with a change in rhythm and 10 unchanged. After hearing two melodies played by a piano synthesizer, subjects were requested to decide if they were same or different during a 4-sec silent period. On average, our subjects obtained a total raw AMMA score of 53.4 (SD = 6.4; range 43–68), a mean raw score for the tonal AMMA of 26.4 (SD = 4.5; range 19–34), and a mean raw score for the rhythm AMMA of 27.1 (SD = 2.8, range 24–34). These scores are comparable with the ones obtained by non-musicians and amateur musicians in previous studies (Schneider et al., 2002; Seppänen et al., 2007). Thus, our subject sample did not differ from normal levels of tonal and rhythmic skills.

2.3. EEG recording and data analysis

The EEG was recorded with a BioSemi ActiveTwo system. A 64-channel cap based on 10/5 system was used with active electrodes, with a sampling rate of 2048 Hz during recordings, down-sampled for data analysis purposes to 512 Hz with BDFDecimator software. Double-sided adhesive electrode rings were used to attach the electrodes to the mastoids behind the auricles and to the EOG (below the lower eyelid of the right eye), and the reference electrodes were attached to the nose.

The EEG was offline filtered (bandpass 1–30 Hz). Epochs of 100 msec pre-stimulus and 400 msec post-stimulus periods were separately averaged for the 6 types of deviant stimuli in each condition and for the standard stimuli, divided into 6 groups preceding each deviant type. The mean voltage of the 100 msec pre-stimulus period served as a baseline for amplitude measurements. The epochs including an EEG or EOG change exceeding ±100 μV for more than 4 isolated channels were omitted from the average. Isolated channels with exceeding range were interpolated. Only few channels were contaminated in some subjects, and these were discarded.

First, the MMN peak latencies were measured from the most negative peak in the deviant ERP waveform compared with the standard waveform, at the frontal electrode approximating the Fz in the 10–20 system and the most positive peaks at the mastoid electrodes (LM and RM) occurring at the 100–200 msec post-stimulus period. These electrodes were chosen on the basis of visual inspection and the previous MMN literature, according to which the largest negative MMN peak is typically obtained at Fz and the largest reversed potential at the mastoid electrodes. The mean ERP amplitudes to the deviant and standard waveforms in the MMN latency window were then calculated as the average voltage at the 40 msec period centered at the individual peak latencies measured from Fz. To determine the significance of the MMN response to each deviant of the musical multi-feature paradigm at the frontal sites and its reversal at the mastoidal sites, two-tailed t tests were conducted contrasting the mean amplitudes measured at Fz, LM and RM in response to the deviant stimuli versus the mean amplitudes to the standard stimuli. Subsequently, to delineate the MMN and to also include the values from the mastoids, the ERPs to standard stimuli (the third note of the standard Alberti pattern) were subtracted from the corresponding deviant-stimulus ERPs of the same sequence and therefore re-referenced to the average values measured from the mastoid channels. This procedure resulted in 6 different waveforms per subject. For further statistical analysis testing, the effects of feature deviation on the MMN amplitudes, latencies and scalp distribution, individual mean MMN amplitudes, and peak latencies were calculated as before. Repeated measures ANOVAs on the MMN mean amplitudes were then performed on a subset of electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). For these ANOVAs, the within-subject factors Deviation (6 levels: pitch, timbre, location, intensity, slide, rhythm), Frontality (3 levels: F-line, C-line, P-line), and Laterality (left, middle, right) were adopted. Finally, the MMN latencies for the 6 deviants as measured from Fz electrode were compared with each other with a one-way ANOVA including Deviation as a factor. For the ANOVAs, Greenhouse–Geisser correction was used and Greenhouse–Geisser ε reported, when appropriate. Corrected *p*-values were reported with uncorrected degrees of freedom.

3. Results

As illustrated in Fig. 2, the fast multi-feature paradigm produced MMNs for all 6 feature deviations, as demonstrated by the significant differences between the mean amplitudes to deviant versus standard stimuli recorded at Fz (Table 1). However, the rhythm and intensity deviants did not elicit a significant positive reversal at the MMN latency as recorded from the mastoid electrodes (Table 1).

As shown by Fig. 3, the MMN latencies were modulated by the feature deviations, $F(5, 50) = 16.3$, $p > .0001$, $\varepsilon = .4$. The MMN with the longest latency was elicited by the pitch-mistuning deviant (M = 198 msec) compared with all the other deviants ($p < .001$ for all; timbre M = 144 msec, location M = 114 msec, intensity M = 154 msec, slide M = 157 msec, rhythm M = 123 msec; note that 30 msec have been added to the individual rhythm latencies to compensate for the onset of the deviant sound event). The MMN with the shortest latency was elicited by the location deviant, which did not statistically differ from the rhythm deviant ($p = .2$ for the latter, and $p < .001$ for the others). Interestingly, however, all MMN parameters, namely latency, amplitude, and topographical distribution, were modulated by the deviating musical feature as revealed by the significant main effect of Deviation, $F(5, 50) = 14.1$, $p < .0001$, and the significant interaction of Deviation with Frontality, $F(10, 100) = 7$, $p < .0001$, $\varepsilon = .3$. These

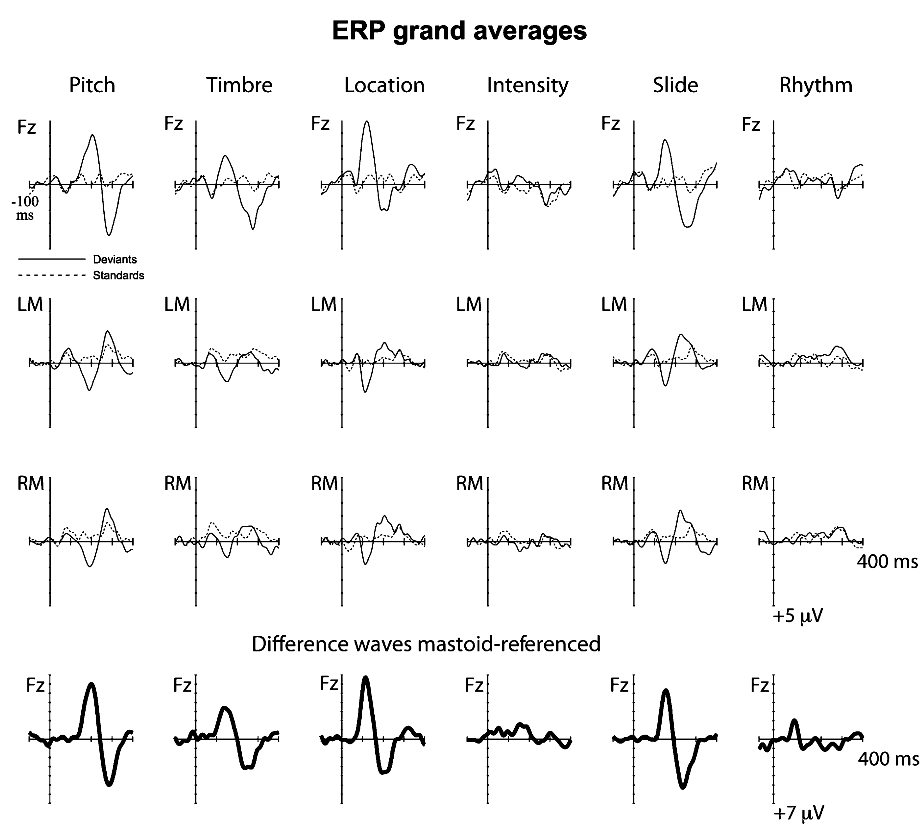


Fig. 2 – Top three lines: grand average ERPs (11 subjects) for 6 types of deviations recorded at a fronto-central (approximately FCz) and two mastoid sites. The dotted line indicates responses to the standards. Bottom line: difference waves for the deviations referenced to the mean of the mastoids. Note that the onset of the rhythm deviant was −30 msec corresponding to the intersection of the y-axis.

Table 1 – Amplitude of the MMNs to different sound features (difference between deviant and standard).

	Reference	Mean voltage (μV)	t	SD	p	Mean latency[a] (msec)
Pitch	Fz	−3.31	−5.81	1.89	.00	195
	LM	2.17	4.34	1.66	.00	
	RM	1.96	3.56	1.82	.01	
Timbre	Fz	−1.90	−3.63	1.74	.01	144
	LM	1.63	5.38	1.00	.00	
	RM	1.23	4.14	.99	.00	
Location	Fz	−4.05	−7.35	1.83	.00	114
	LM	1.84	3.55	1.71	.01	
	RM	1.57	3.32	1.57	.01	
Intensity	Fz	−1.47	−2.69	1.81	.02	155
	LM	.25	.88	.92	.40	
	RM	.26	.91	.95	.30	
Slide	Fz	−3.15	−4.73	2.21	.00	157
	LM	1.40	5.47	.85	.00	
	RM	1.72	4.64	1.23	.00	
Rhythm	Fz	−1.05	−3.79	.92	.00	131
	LM	.21	.60	1.18	.56	
	RM	.02	.06	1.06	.95	

a Main effect of feature deviation in one-way ANOVA: $F(5, 50) = 15.1$, $p > .0001$, $\varepsilon = .3$.

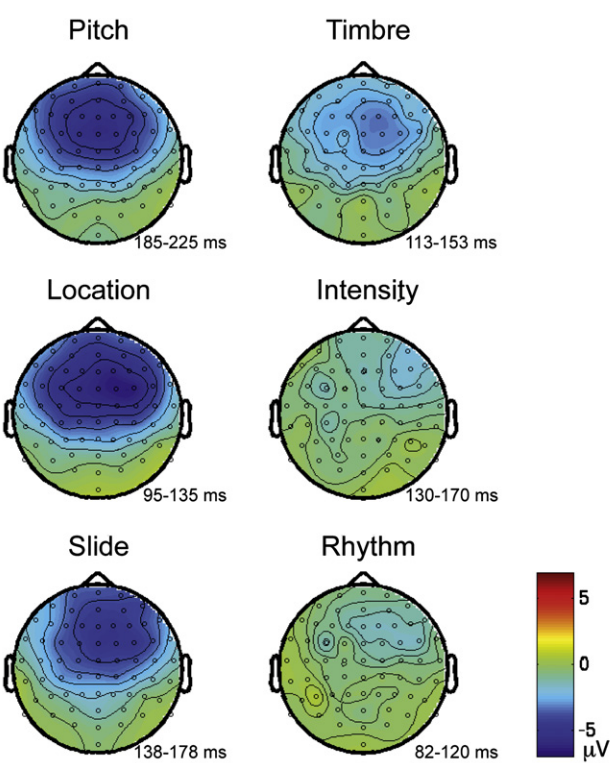


Fig. 3 – EEG voltage isopotential maps of the difference between the responses to deviants and standards averaged in an interval of ±20 msec around maximal peak amplitudes.

findings are illustrated by the different waveforms and voltage maps presented in Fig. 3.

As demonstrated in Fig. 3 and by separate two-way ANOVAs for the Deviation factor, the pitch MMN was larger in amplitude at the frontal region compared with the central and parietal regions [main effect of Frontality: $F(2, 20) = 68.2$, $p < .0001$, and $p < .001$ in post-hoc LSD tests (Fisher's least significant difference test)]. The timbre MMN was instead fronto-centrally distributed [main effect of Frontality: $F(2, 20) = 16.7$, $p = .001$, $\varepsilon = .6$; and $p < .01$ in post-hoc tests comparing frontal and central values to the parietal one; no difference between MMN recorded at frontal and central regions], and left-lateralized at parietal regions, as shown by the significant interaction of Frontality × Laterality, $F(4, 40) = 2.7$, $p = .04$ and by the significant t-test between values at P3 versus P4, $t(10) = -2.3$, $p < .05$ (see Fig. 3). A fronto-central distribution was also observed for the location MMN [main effect of Frontality: $F(2, 20) = 15.9$, $p = .001$, $\varepsilon = .6$; and $p < .01$ for the post-hoc tests comparing frontal and central values to the parietal one; no difference between the frontal and central values; Fig. 3]. Similar to the pitch MMN, the intensity MMN was frontally maximal [main effect of Frontality: $F(2, 20) = 18.6$, $p < .0001$], however, a significant interaction Frontality × Laterality was also observed, $F(4, 40) = 4.4$, $p = .005$, resulting from a larger negativity at the right side compared to the left in the frontal region [t-test comparing F3 *vs* F4: $t(10) = 2.6$, $p = .03$; Fig. 3]. The slide MMN was also maximal at the frontal regions compared with the central and parietal ones [main effect of Frontality: $F(2, 20) = 16.4$, $p = .001$, $\varepsilon = .6$, post-hoc tests with $p < .02$ for the comparisons between MMN values at the frontal *vs* central and parietal electrodes] and with a tendency for lateralization to the right hemisphere [main effect of Laterality: $F(2, 20) = 3.1$, $p = .065$]. Finally, the rhythm MMN was maximal in amplitude at the frontal regions [main effect of Frontality: $F(2, 20) = 15.2$, $p < .0001$ and $p < .01$ in post-hoc LSD tests] with no laterality effects (Fig. 3).

To further test the MMN scalp distribution, we performed direct comparisons of the MMN amplitudes for all the deviations in left and right hemispheric sites. At the left electrodes, we obtained a main effect of Deviation, $F(5, 50) = 13.3$, $p < .0001$, and a significant interaction of Deviation × Frontality, $F(10, 100) = 5$, $p = .005$, $\varepsilon = .3$. Subsequent pairwise t-tests revealed that this interaction was derived from the smallest frontal MMNs to intensity and rhythm MMN compared with those to the other deviations (in pairwise comparisons, $p < .03$) with the other frontal MMNs which were not statistically different from each other. Then, at left central electrodes, the MMNs to intensity and rhythm were diminished compared with all the others ($p < .04$), but with MMN to intensity not differing from that to timbre. Instead, the left parietal MMN to rhythm was reduced only as compared with the MMN to pitch and location ($p < .03$), and the MMN to location, besides being larger than that to rhythm exceeded that to timbre ($p = .03$). At the right electrodes, we also found a significant main effect of Deviation, $F(5, 50) = 12$, $p < .001$, and a significant interaction of Deviation × Frontality, $F(10, 100) = 5.4$, $p = .001$, $\varepsilon = .4$. As shown by subsequent pairwise t-tests, this interaction was due to the smallest right frontal and central MMN in rhythm compared with other deviations ($p < .03$), except for the MMN to the intensity deviant.

Moreover, at right frontal and central electrode sites, the MMN amplitudes to location and slide (and also to pitch for frontal sites) were larger than those to timbre, intensity, and rhythm deviations ($p < .03$). Finally, at right parietal scalp regions, the largest MMN negativities were elicited by pitch, location, and slide deviants ($p < .05$) and the smallest, once again, by the rhythm, intensity and timbre deviants ($p < .05$), with the timbre MMN not differing from the pitch MMN.

4. Discussion

In a novel, fast, musical, multi-feature paradigm, we have found that deviations of sound aspects of notes embedded in a prototypical musical pattern, which are important for music perception, can elicit distinct MMNs. This paradigm presents itself as a possible objective measure of auditory skills relevant to music perception, since MMNs are pre-attentively elicited with no behavioral task, and are correlated with individual behavioral measures and musical expertise (Nikjeh et al., 2009; Pantev et al., 2003; Russeler et al., 2001; Vuust et al., 2005). Moreover, the study combines the multi-feature MMN-technique with musical stimuli, suggesting that even when listening to more musical sounding stimuli, attention-independent processes, as indicated by MMNs, may play an important role.

Compared with previous musical MMN-studies, our paradigm is advantageously short. Using the multi-feature approach, it was possible to record MMNs to 6 features in 20 min, which is the same amount of time needed to record one musical feature using the previous paradigms with temporally complex musical stimuli (Brattico et al., 2006; Tervaniemi et al., 2001; Van Zuijen et al., 2004; Vuust et al., 2005). For instance, the recording time for rhythmic incongruities in an ecological drum rhythm used in Vuust et al. (2005) was 6 times 15 min excluding breaks. Despite the fact that we needed to make the stimulus more complex than Näätänens multi-feature paradigm, we still obtained a short duration for the paradigm. When considering behavioral tests used for testing selected tonal and rhythmic aspects of subjects' musical potential or aptitude, such as the AMMA test (Gordon, 1989) lasting 15 min, or the newly developed Musical Ear Test (MET-test) (Wallentin et al., 2010) with a duration of 20 min, the musical multi-feature paradigm is comparatively short. In addition to providing an objective measure of musical skill levels, our new paradigm allows one to probe the neural mechanisms underlying these musical skills. Finally, compared to previous studies focusing on musical processing (Brattico et al., 2006; Tervaniemi et al., 2001), this paradigm includes acoustic variation, such as transpositions over various frequency levels.

In their present form, the amplitudes of the MMNs of the different deviants are not yet in perfect balance, especially regarding the rhythm and intensity deviants. This is due to the size of the different deviations as well as the individual differences between subject groups as argued above. Nevertheless, the deviants of this paradigm could and should be adjusted according to the purpose of use. In order to reveal differences between groups of musicians, it would probably be advisable to use near-threshold stimuli such as the present intensity and rhythm deviants. In the present study, a borderline threshold level of 30 msec was chosen for the rhythm deviant. Musicians, but not non-musicians, have shown MMNs for deviants of 20 msec, whereas non-musicians have a higher threshold for responding to rhythmic deviations (Russeler et al., 2001). A future study will focus on differences between different musical experts in pre-attentive discrimination of musical features.

Three of the six deviants (pitch, location and intensity) used in the present study were also embedded in the less complex auditory sequences of previous multi-feature MMN-studies (Näätänen et al., 2004; Pakarinen et al., 2007). Pakarinen et al. previously compared the MMNs to six different magnitudes of the deviations, and provided a possible point of reference regarding MMN amplitude and latency. The MMNs to the pitch deviations are not directly comparable between the two studies, however, since the relationships between standards and deviations in the present study are defined according to the musical scale: the pitch deviation always corresponds to a quarter note (1/2 of a semitone, regardless of the absolute frequency values) such that this musical-scale relationship is perceived similarly in different musical keys. The quartertone deviation in our study falls between level 2 (1/3 of a semitone) and level 3 (6/8 of a semitone) in the Pakarinen et al. study, and the corresponding amplitude of the MMN also falls within the range of amplitudes of the MMNs in the Pakarinen et al. study ($-2.1\,\mu V < -3.3\,\mu V < -\ 3.6\,\mu V$, nose-referenced). The latency is slightly longer in our study (195 msec compared to 160–180 msec in the Pakarinen et al.'s study). This indicates that for pitch deviation, the more complex context of the present study does not attenuate the amplitude, rather, it slightly prolongs the latency of the MMN. In a study by Brattico et al. (2001), a similar longer MMN latency for pitch deviations was observed in a temporally complex compared with a simple context. Hence, the complexity of the local context of the pitch deviant seems to affect the MMN latency. This observation corresponds with the hypothesis that pitch relations are culturally encoded in long-term memory (Brattico et al., 2006; Krumhansl, 1990; Leman, 1995) and it may also be the reason why the slide deviant, which is also related to pitch processing, elicits a relatively strong and fast MMN in the present study.

The location deviant in the present study was created in a different way than in the Pakarinen et al. study, however the MMN amplitude in the present study is comparable to the one obtained for the second highest level in the Pakarinen study (4.1 μV compared to 4.3) corresponding to a 60° deviation in the Pakarinen et al. study and the latency of this deviation is somewhat smaller than in the Pakarinen et al. study (114 msec compared to around 140 msec). This difference, however, could be due to the fact that the present location deviant was constructed by a difference in loudness between left and right calling for a fundamentally different neural processing (Schnupp and Carr, 2009) than the time difference used in the Pakarinen et al. study. Finally, the MMN to the intensity deviant in our study (6 dB lower than the standard, amplitude $-1.47\,\mu V$) is considerably lower than the MMNs to intensity in the Pakarinen et al. study ($-3.4\,\mu V$, for a 5 dB deviation). This indicates that the complexity of the paradigm influences the MMN to the intensity deviant in particular. A possible reason for this may be that there is an interaction between the changing pitches in the present paradigm and the perceived intensity (Paavilainen et al., 2001). Taken together, the complexity of the present paradigm influences the MMNs to some of the deviants more than others, which may also explain the reason that the deviants of the present paradigm are yet not perfectly balanced.

The differences in the MMN scalp distributions and latencies between the different deviant types observed in the present study extend previous results suggesting that partially separate MMN generators for different sound features reflect separate processing in auditory sensory memory of pitch, timbre, intensity, timing and location (Alho, 1995; Caclin et al., 2006; Giard et al., 1990; Näätänen and Winkler, 1999). Further, the MMNs to different sound features have temporal or frontal generators, or both. In our study, we found significant MMNs at mastoid electrodes, indicating a locus for the underlying generators at the primary and non-primary auditory cortices, with the exception of MMNs to intensity and rhythm deviants (likely due to their lower voltage amplitudes). Moreover, we observed a right lateralization for the intensity MMN, and to a lesser extent, the slide MMN. These observations are consistent with the hypothesis that current sources of the MMNs to different sound features are differently localized in the brain, or that they have different orientations.

The musical multi-feature paradigm constitutes a development of the multi-feature paradigm, formulated by Näätänen and colleagues, in a musical direction. In contrast to the original multi-feature paradigm consisting of repeated tones only varied by the deviants, the “Alberti bass” of the present study provides an arpeggio-like texture that is used in different genres of music to provide the harmonic background for a melody. The randomization of keys follows a principle similar to what is used in twelve tone music in which each of the twelve notes appears exactly once, only here as a chord progression. This kind of random chord plateaus have been used frequently in modal jazz, e.g., in the composition “Sketches of Spain” from Miles Davis’ Kind of Blue, where there is no apparent relation between different plateaus of modalities. Thus, the musical multi-feature paradigm is by construction definitively more musical than Näätänen et al.’s (2004) multi-feature paradigm, however, it admittedly lacks both melody and intentionality. Future studies should be conducted to determine if adding melody and potentially a composer’s touch would still allow for pre-attentive processing that can be detected with MMN. Even so, for the purpose of comparing MMNs in musicians from different musical genres, extending the multi-feature paradigm to encompass more complex stimuli such as the ones pursued in our study may prove to be crucial since stimulus complexity might be required to disclose fine-grained auditory processing differences between participants from various musical backgrounds (Huotilainen et al., 2009; Koelsch et al., 1999; Seppänen et al., 2007).

The musical multi-feature MMN paradigm could potentially be of particular interest to music education. For instance, in the case that future developments of the ERP-method will reach sensitivity and reliability even at the individual level, (whereas currently ERPs are sensitive and reliable only at the group level,) it may be possible to draw individual multi-attribute ‘profiles’ of sound-discrimination abilities. Consequently, if EEG facilities would be available in music departments, as they are in some European universities, teachers could complement their behavioral test observations with fast ERP recordings, hence tailoring individual ear-training on the basis of individual auditory neural aptitudes. On the other hand, caution should be taken in advocating “objective” auditory measures as the sole basis for recruiting and evaluating musical students. Musical abilities depend on a number of different factors which are difficult to measure objectively (Vuust et al., 2010; Woody and Mcpherson, 2010), such as having a characteristic individual style, rehearsal stamina, creativity, and motivation.

5. Conclusion

Here we present a novel multi-feature MMN paradigm with significant MMNs to 6 different deviant types integrated in a complex musical context of no more than 20 min in duration. This short objective measure can putatively be used for studying auditory and musical development.

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