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Mismatch negativity to single and multiple pitch-deviant tones in regular and pseudo-random complex tone sequences

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Abstract

Objectives: To determine whether the process responsible for the mismatch negativity (MMN) might be involved in the analysis of temporal sound patterns for information.

Methods: Synthesized musical instrument tones of 'clarinet' timbre were delivered in a continuous sequence at 16 tones/s, such that there was virtually no N1 potential to each individual tone. The standard sequence comprised 4 or 5 adjacent notes of the diatonic scale, presented either as a regularly repeated, rising pattern or pseudo-randomly. The deviant stimuli were 1–5 consecutive tones of higher pitch than the standards.

Results: A MMN was evoked by a single deviant tone, 1 or 5 semitones above the pitch range of the standards. The response to the 5-semitone deviant was significantly larger (mean of 7.3 μV) when the standard pattern was regular as compared with pseudo-random. The MMN latency, on the other hand, was only influenced by the magnitude of pitch deviation. A second MMN was evoked by a second deviant tone, immediately (SOA 62.5 ms) following the first. Further consecutive MMNs were not consistently evoked.

Conclusions: The large amplitude of these MMNs can be attributed to the use of complex tones, continuous presentation and a rapid rate of pitch changes, such that no waveform subtraction was required. Over and above the probability with which each individual tone occurs in the standard sequence, the mismatch process is influenced by its temporal structure, i.e. can be regarded as a temporal pattern analyzer. Contrary to the findings of some other groups, we found that two consecutive deviants can evoke an MMN, even at high rates of presentation such that both occur within the postulated 'temporal window of integration' of ca. 170 ms. These findings suggest that the mismatch process might be involved in the extraction of sequential information from repetitive and non-repetitive sound patterns. © 2002 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Auditory evoked potential; Auditory cortex; Complex tones; Mismatch negativity; Sound pattern analysis

1. Introduction

Perhaps to a degree unique amongst land mammals, the human auditory system is highly adapted to extract information from rapid sound sequences. The mismatch negativity (MMN) is a well-known component of the auditory event-related potential, believed to represent pre-attentive processes involved in the detection of change in sequences of sounds (e.g. Näätänen, 1995; Csépe, 1995; Näätänen and Alho, 1997). Various suggestions have been made regarding the functional significance of the MMN, including attentional orientation to novel stimuli and maintaining the internal representation of auditory constancies. In this study we examine whether the generator of the MMN might also be involved in the analysis of sound for information. One of the ways in which a sound can produce an MMN is by deviating in some way from a repeating temporal pattern (e.g. Nordby et al., 1988; Schröger et al., 1992; Schröger, 1994; Alho and Sinervo, 1997; Alain et al., 1998; Tervaniemi et al., 2001). If the repeating pattern is regarded as a 'carrier' signal (analogous to a radio wave), then the deviants may be considered the 'information' which is being carried.

In previous studies (Vaz Pato and Jones, 1999; Jones et al., 2000) we used continuous synthesized musical instrument tones that oscillated between two pitches at a rate rapid enough (16 notes/s) practically to abolish the 'change-type' N1 and P2 potentials associated with each individual change. When the oscillating pattern came to rest on a steady tone, a negative potential was evoked with a more anterior scalp distribution than the CN1 to individual changes, and with a latency apparently determined by the expected time of the next change, which did not in fact occur. This negative potential, we argued, is likely to be

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closely related if not identical to the MMN, being the expression of a process by which the immediate sound is compared with a template of the oscillatory pattern, extrapolated so as to predict when the next change should occur and possibly even what that change should be. Conceptually, the circumstances are similar to those of a 'duration deviant', by which an MMN is produced without any increase in the amplitude of the N1 (Picton et al., 2000). The amplitude of the potential was strongly influenced by the duration of the preceding oscillation up to 4.5 s or more (Jones et al., 2000), suggesting the participation of a memory store which accumulates sounds over this period (Cowan, 1984). These responses to continuously presented, spectrally complex tones were substantially larger than the conventional MMN to discontinuous pure tones, and were obtained without the need for off-line waveform subtraction.

In order to clarify what factors influence the MMN, we compared the responses occurring at the end of regularly repeating and pseudo-random sequences (Vaz Pato and Jones, 1999). On resumption of a steady pitch after 2 s of a repeating pattern of two to 5 tones, the MMN amplitude averaged between 6 and 8 μV. After a sequence in which the same 5 tones were presented in pseudo-random order the response was slightly but not significantly smaller. This prompted us to assess the importance of temporal structure in the mismatch process. Do identical pitch-deviant tones occurring in periodic and non-periodic sequences produce identical MMNs, provided the pitches encompassed by the standard sequence are the same? If the temporal structure of the sound pattern is an influential factor, the detection of deviation might serve as more than an orienting mechanism or call to attention, and could be involved in the analysis of temporal sound patterns for information. Moreover, if the process can be shown to repeat itself with successive deviants at a high rate of presentation, this would also argue against its sole function being attentional orientation.

The objectives of the present study therefore were:

1. To assess the influence of the temporal structure of the standard sequence on the MMN elicited by pitch-deviant tones.
2. To see whether, in a rapid, regularly repeating pattern, multiple MMNs may be generated by two or more consecutive tones deviating from the expected pitches.

2. Methods

Ten normally hearing, right-handed volunteers (5 males and 5 females, aged 21–49 years) participated in the first experiment. In the second experiment 9 subjects (4 males and 5 females with the same age range) participated. All gave their informed consent according to the Declaration of Helsinki. The subjects sat in an armchair and read a book for the duration of each experiment, which was approximately 60 min. The only instructions given were to relax and read continuously, and no verbal response was required.

Ten recording electrodes were attached to the scalp with paste, on the midline at Fpz, Fz, Cz, Pz, and at lateral locations F3, C3, T3, F4, C4 and T4 of the 10–20 system. The reference electrode was on the dorsum of the neck at the base of the skull. The amplifier bandwidth was between 1 and 200 Hz, the averaging epoch was 600 ms and the A/D conversion rate was 2 kHz. The pre-stimulus baseline period was 50 ms. The recording apparatus comprised an IBM-compatible Gateway 2000 laptop computer running Signal software (CED, Cambridge) which controlled a CED 1401 Plus analog/digital converter and CED 1902 amplifiers.

The stimuli were created by a Yamaha MU10 tone generator controlled by an IBM-compatible Daewoo laptop computer. The software used to construct and play stimulus sequences was Midisoft Recording Studio (Diamond Computer Systems) and Cubasis (Steinberg Soft and Hardware), respectively. The left and right output channels were split in order to use one channel for the stimulus (presented binaurally through headphones) and the other to trigger the recording apparatus after conversion to a TTL pulse. All sounds had a smooth onset and offset with a rise-time of approximately 10 ms (established by examination of their waveforms; this was also done to establish the precise temporal relationship between stimulus and trigger) and approximately 20 ms of overlap between consecutive tones. The tones were played in 'clarinet' timbre, chosen on account of its unexaggerated onset and subsequent steady intensity and pitch. The sound spectra (illustrated in a previous paper; Jones and Perez, 2001) were analyzed using a fast analog/digital converter and associated software (Pico Technology, Cambridge, UK). The tones were labeled according to western musical notation, A4 pitch corresponding to a fundamental frequency of 440 Hz and changes of one semitone equivalent to approximately 5.9% in frequency terms. The intensity was 45–50 dB above threshold. Tones were presented continuously, each 62.5 ms in duration. Responses were measured at the Fz location where the MMN was most prominent. Amplitudes were measured from the pre-stimulus baseline. Response amplitudes and latencies were analyzed and compared using analysis of variance (ANOVA). Bonferroni-corrected t tests were used for paired comparison of individual conditions.

2.1. Experiment 1

The standard sequence comprised 4 adjacent notes of the diatonic scale; F4, G4, A4 and B4, two semitones apart. Each note was presented 20 times (total duration 5000 ms) and on the 21st repetition the first tone was replaced by a deviant tone of higher pitch. Responses were recorded to 14 deviants and each condition was repeated 3 times, making a total of 42 responses in the grand average computed for each subject. In the first two conditions, REG1 and REG2, the

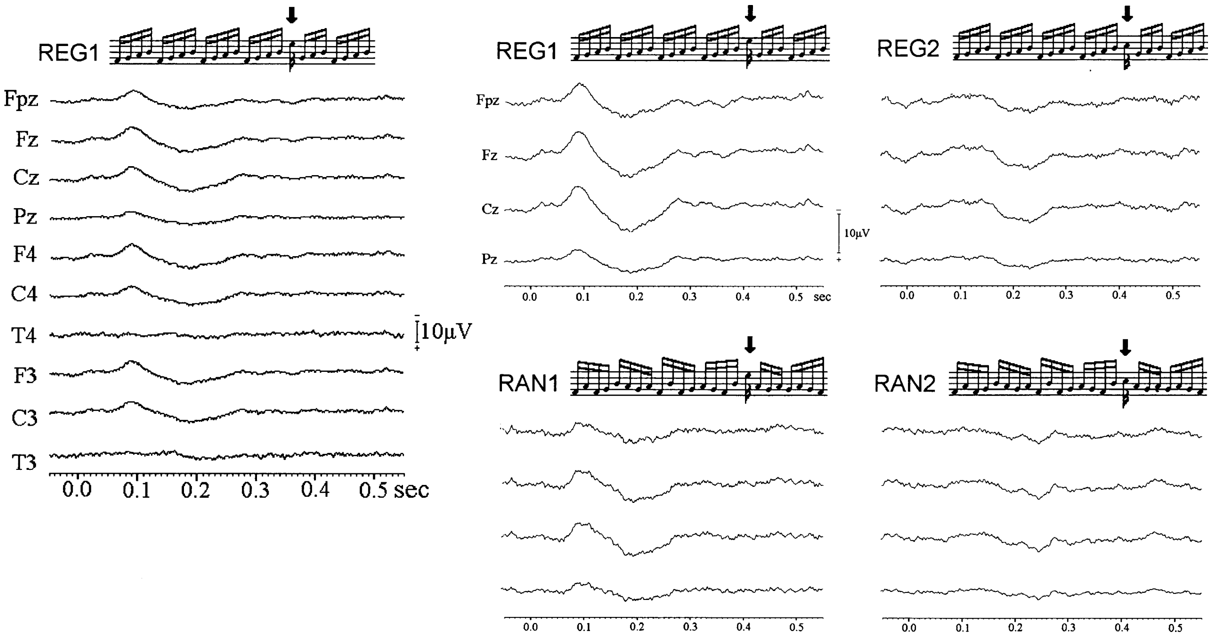

Fig. 1. Experiment 1. Left: group mean waveforms at all 10 electrodes of the response to the widely pitch-deviant tone in the regular 4-tone, 16 tones/s sequence (REG1). Right: group mean waveforms at the 4 midline scalp electrodes to the widely (REG1, RAN1) and narrowly deviant tones (REG2, RAN2) in the regular and pseudo-random 4-note sequences.

tones of the standard sequence were arranged in a regularly repeated, rising pattern F4, G4, A4, B4. In REG1 the deviant involved replacement of the F4 tone by E5, 11 semitones above the expected note and 5 semitones above the highest note in the sequence. In REG2 F4 was replaced by a deviant C5, 7 semitones above the expected note and only one semitone above the highest in the sequence (Fig. 1). In the 3rd and 4th conditions, RAN1 and RAN2, the standard sequence comprised the same notes ordered pseudo-randomly with no discernible rhythmic pattern. The 'randomness' of the sequence was constrained by the stipulation that each tone should occur 20 times in the 5000 ms preceding the deviant, and the same tone should not occur twice in succession. The deviants were the same tones of higher pitch, E5 and C5, occurring at the same points in each cycle.

2.2. Experiment 2

In the second experiment the standard sequence was a regular, rising pattern of 5 adjacent notes of the diatonic scale – F4, G4, A4, B4 and C5. The sequence was repeated 15 times (total duration of 4687.5 ms) and on the 16th repetition some or all of the notes in the sequence were replaced by deviants of higher pitch. The overall cycle was repeated 24 times and 3 averages were obtained per condition, making a grand average of 72 responses to each deviant. The deviant tones had the effect of extending the rising scale by 1, 2, 3, 4 or 5 notes. In condition DEV1 F4 was substituted by D5, in DEV2 F4 and G4 were substituted by D5 and E5, in DEV3 F4, G4 and A4 were substituted by D5, E5 and F5, in DEV4 F4, G4, A4 and B4 were substituted by D5, E5, F5 and G5, and in DEV5 F4, G4, A4, B4 and C5 were substituted by D5, E5, F5, G5 and A5 (Fig. 3). In order to examine the effect of deviant tones subsequent to the first, digital subtractions were made of the grand average responses for each subject: DEV2 minus DEV1, DEV3 minus DEV2, DEV4 minus DEV3 and DEV5 minus DEV4. For each subject, the isolated responses to the second deviant (DEV2 minus DEV1) and the first (DEV1)

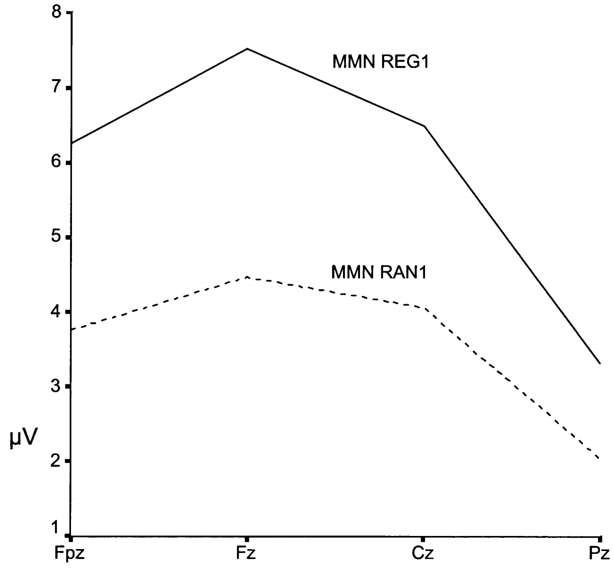

Fig. 2. Experiment 1. Amplitude distribution (midline electrodes) for REG1 and RAN1.

were compared using paired *t* tests. Responses to subsequent deviants were not consistently obtained, and were not analyzed statistically.

3. Results

3.1. Experiment 1

In all 4 conditions – regular and pseudo-random 4-note sequences with wide and narrow pitch deviants – the response to the deviant tone consisted of a negativity peaking at 100–140 ms and a positivity at 180–225 ms. Since there was no perceptible response to each individual tone of the standard sequence, the negativity was presumed to be largely if not entirely an MMN (arguments justifying this assumption are detailed in Section 4). The responses were of maximal amplitude at Fz and symmetrically distributed, as illustrated by the group mean responses (Fig. 1) and the profile of MMN amplitudes at mid-sagittal electrodes (Fig. 2). Table 1 gives the means and standard deviations of amplitude and latency in each condition, measured at Fz. Measurable potentials were obtained in all 10 subjects for REG1 (regular sequence, wide deviant), in 9/10 subjects for REG2 (regular sequence, narrow deviant) and RAN1 (pseudo-random sequence, wide deviant), and in 8/10 subjects for RAN2 (pseudo-random sequence, narrow deviant).

A two-way ANOVA was performed on the amplitude values of all 10 subjects (absent responses being recorded as zero) and on the latency values of the 7 subjects with complete data. Both the amplitude and the latency of the MMN and the following positivity (termed MMP) were significantly influenced by the stimulus condition (MMN amplitude $F(3,27) = 11.409$, $P = 0.00005$; MMN latency $F(3,18) = 8.435$, $P = 0.001$; MMP amplitude $F(3,27) = 3.495$, $P = 0.029$); MMP latency $F(3,18) = 8.722$, $P = 0.0004$).

In accordance with the number of subjects in whom the MMN was measurable, on average the potential was largest for REG1 (7.3 μV), intermediate for RAN1 (4.0 μV) and REG2 (3.7 μV), and smallest for RAN2 (1.5 μV). Post hoc paired *t* tests compared REG1 with RAN1 and REG2 with RAN2 in order to determine the effect of repetitive temporal structure, and REG1 with REG2 and RAN1 with RAN2 in order to determine the effect of the degree of pitch deviance. A Bonferroni-correction factor of 4 was applied to the probabilities. A significant difference was found between REG1 and RAN1 ($t = 4.767, P = 0.004$), indicating that the MMN to a widely pitch-deviant tone was larger in the context of a regularly repeating pattern than in a pseudo-random pattern of the same pitches. Although the amplitude difference between REG1 and REG2 (wide versus narrow pitch-deviant tones in a regular pattern) was of similar magnitude to that between REG1 and RAN1, the difference was just non-significant after Bonferroni correction ($t = 3.047$, $P = 0.056$). The other two comparisons were also non-significant.

On average, the MMN latency was substantially shorter for widely deviant tones (ca. 100 ms, REG1 and RAN1) as compared with narrow deviants (ca. 135 ms, REG2 and RAN2, Table 1). The difference between REG1 and REG2 was significant after Bonferroni correction ($t = 4.211$, $P = 0.012$), as was the difference between RAN1 and RAN2 ($t = 5.499, P = 0.008$), indicating a similar effect of the degree of pitch deviance for both regular and pseudo-random patterns. Latency differences between regular and pseudo-random conditions with the same deviant tone were not significant.

The MMP amplitude was also on average largest for REG1, intermediate for RAN1 and REG2 and smallest for REG2 (Table 1), although in Bonferroni-corrected *t* tests the differences were all non-significant. As with the MMN, MMP latencies were shorter on average for wide deviants (ca. 190 ms, REG1 and RAN1) as compared with narrow deviants (ca. 220 ms, REG2 and RAN2). The difference in MMP latency between REG1 and REG2 was statistically significant after Bonferroni correction ($t = 4.740$, $P = 0.004$), as was the difference between RAN1 and RAN2 ($t = 4.509$, $P = 0.016$). Comparisons between regular and pseudo-random conditions with the same deviant tone were non-significant.

3.2. Experiment 2

The second experiment compared the responses to 1, 2, 3, 4 and 5 consecutive pitch-deviant tones, SOA 62.5 ms, in a regularly repeating cycle of 5 different pitches. Measurable potentials were obtained in all 9 subjects. Fig. 3 shows the group mean responses at the 4 mid-sagittal electrodes in

Table 1
Experiment 1: mean ± standard deviation of amplitude and latency values for MMN and MMP to widely (REG1, RAN1) and narrowly (REG2, RAN2) deviant tones following regular and pseudo-random 4-note sequences

	MMN		MMP	
	Amplitude (μV)	Latency (ms)	Amplitude (μV)	Latency (ms)
REG1	−7.3 ± 1.9	100.0 ± 18.1	5.5 ± 2.2	184.7 ± 20.4
REG2	−3.7 ± 3.0	132.9 ± 29.0	3.5 ± 1.9	216.8 ± 22.2
RAN1	−4.0 ± 1.9	103.1 ± 20.6	4.7 ± 3.0	190.8 ± 29.1
RAN2	−1.5 ± 1.4	136.1 ± 29.8	2.8 ± 2.2	222.9 ± 30.0

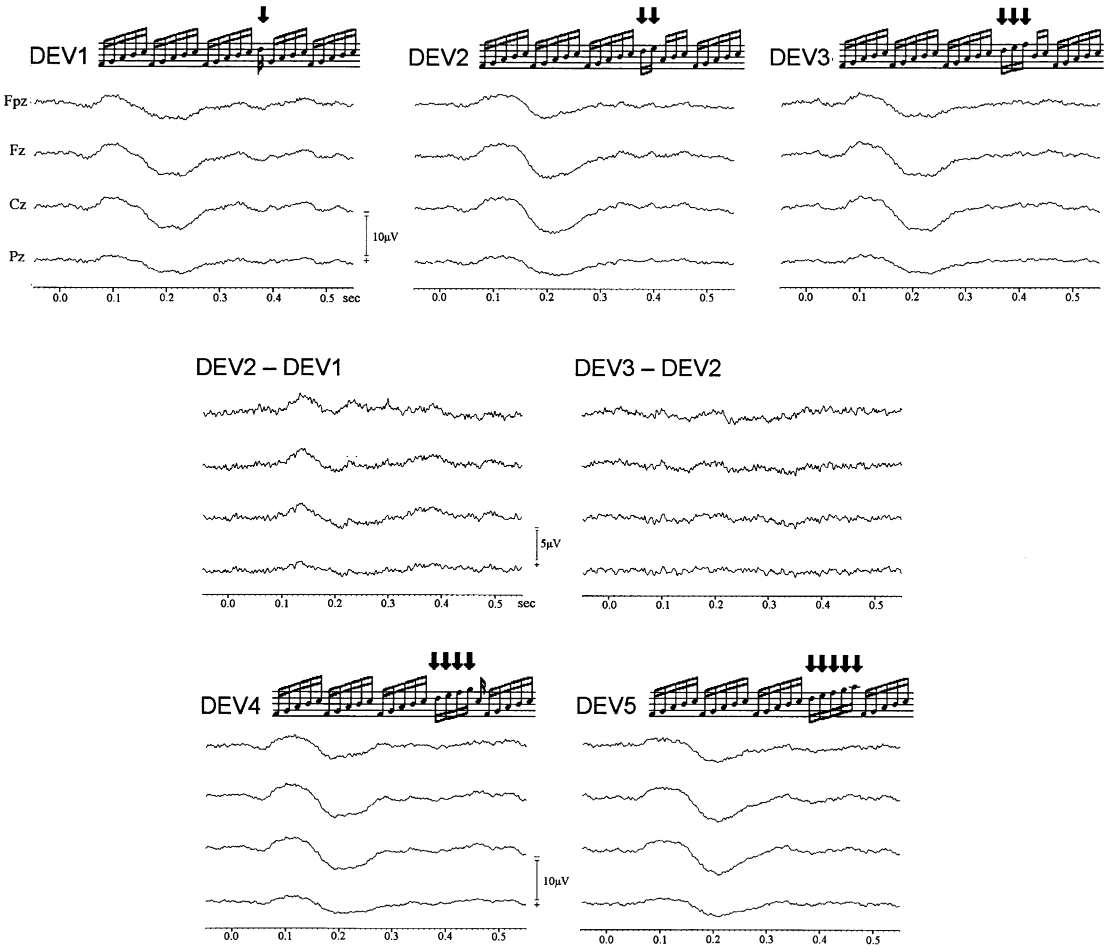

Fig. 3. Experiment 2. Group mean responses to 1–5 successive deviants in a regular 5-tone, 16 tones/s sequence, recorded at the 4 midline scalp electrodes. Also shown are group mean difference waveforms of the response to one deviant (DEV1) subtracted from the response to two successive deviants (DEV2) and the response to two deviants (DEV2) subtracted from the response to 3 successive deviants (DEV3).

each condition. Means and standard deviations of the amplitude and latency of the initial negative and positive peaks, termed MMN and MMP, are given in Table 2. ANOVA revealed no significant differences in amplitude or latency across the 5 conditions (MMN amplitude $F(4,40) = 1.445$, $P = 0.237$; MMN latency $F(4,40) = 1.294$, $P = 0.289$; MMP amplitude $F(4,40) = 0.354$, $P = 0.840$; MMP latency $F(4,40) = 1.209$, $P = 0.322$).

In the DEV1 condition the response to a single deviant, two semitones higher than the highest in the standard sequence and 9 semitones higher than the expected pitch, was again of maximal amplitude at Fz (Fig. 4) and symme-

Table 2

Experiment 2: mean ± standard deviation of amplitude and latency values for MMN and MMP in DEV1–DEV5 (1–5 consecutive deviant notes), and of MMN2 and MMP2 following the second deviant tone in DEV2, after subtraction of DEV1

	Amplitude (μV)	Latency (ms)	Amplitude (μV)	Latency (ms)
	MMN		MMP	
DEV1	−3.2 ± 2.1	94.0 ± 11.5	6.4 ± 2.9	197.7 ± 17.7
DEV2	−4.0 ± 2.4	88.2 ± 13.7	6.1 ± 2.5	205.3 ± 14.3
DEV3	−5.2 ± 1.7	102.2 ± 11.5	5.7 ± 2.8	204.4 ± 19.5
DEV4	−3.5 ± 1.6	93.0 ± 12.3	6.2 ± 2.1	192.4 ± 14.1
DEV5	−3.3 ± 2.0	94.2 ± 17.1	7.1 ± 3.2	206.8 ± 17.2
	MMN2		MMP2	
DEV2−DEV1	−4.0 ± 1.7	139.9 ± 11.2	2.2 ± 1.9	215.9 ± 34.8

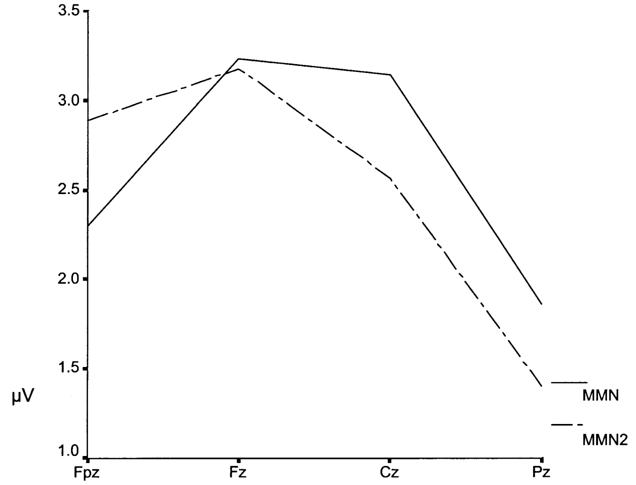

Fig. 4. Experiment 2. Amplitude distribution (midline electrodes) for MMN and MMN2.

trically distributed. In the subtracted waveform, DEV2 minus DEV1, a negativity denoted MMN2 was present in every subject, also maximal at Fz. The mean amplitude of the MMN2 was not significantly different from that of the MMN in DEV1 ($t = 1.517$, $P = 1.344$), although the MMP2 was markedly smaller than the MMP. The mean ± SD of the latency difference between the MMN2 in DEV2 − DEV1 and the MMN in DEV1 was 45.8 ± 21.7 ms. An MMN3 potential was arguably present in the DEV3 − DEV2 subtracted waveforms of some individuals, but was too inconsistent for reliable measurement. No measurable responses were present in the DEV4 − DEV3 and DEV5 − DEV4 subtracted waveforms.

4. Discussion

In a recent review, Picton et al. (2000) identified 5 criteria by which the MMN to a deviant sound may be differentiated from the enhancement of the N1 which also frequently occurs. First, the N1 enhancement does not occur to deviants of longer duration than the standards; this criterion is not applicable to the present study, but supports our contention that the negativity evoked on resumption of a steady pitch after a period of rapid pitch changes is equivalent to the MMN (Vaz Pato and Jones, 1999). This potential and the following positivity were of similar morphology, latency and distribution to those of the present study.

The second criterion of Picton et al. (2000) was that the N1 decreases in amplitude as the interval between the stimuli decreases, whereas the MMN does not. In the present study, 'change-type' N1 responses to tones in the standard sequence were effectively abolished at 16 changes/s, hence the large negativity evoked by tones of deviant pitch seems much more likely to be an MMN. It might be argued that the response to the deviant tone represented a CN1 generated by a new population of pitch-specific neurones, not significantly activated by the standard sequence and therefore not made refractory by the high rate of stimulation. However, the CN1 was previously (Jones et al., 1998) found to be of similar amplitude for pitch changes from 1 to 12 semitones, and for changes of timbre as well as changes of pitch, suggesting that it is change per se rather than change to a tone of a particular frequency that causes the response. In a recent study (Jones and Perez, 2001), the CN1 was not found to be influenced to a large degree by the time between occurrences of the same pitch (as would be expected if the generator were substantially pitch specific), but rather by the time interval between pitch changes. Although single units in the mammalian and human auditory cortex are sharply frequency tuned for tones of threshold intensity, they exhibit a much lower degree of frequency specificity for tones of moderate intensity, their response area typically spanning an octave (12 semitones) or more at intensities of 40–45 dB (Schreiner and Mendelson, 1990; Phillips et al., 1994; Howard et al., 1996). One early animal study (Whitfield and Evans, 1965) found units to be strongly driven by frequency modulations of only a few percent.

The third criterion of Picton et al. (2000), also borne upon by the arguments of the above paragraph, was that the MMN is more specific to changes in stimulus attributes than the N1; therefore, although the widely pitch-deviant tones of REG1 and RAN1 might conceivably have caused some N1 enhancement in addition to an MMN, the narrow pitch deviants of REG2 and RAN2 are likely only to have produced an MMN. Fourthly, according to Picton et al. (2000), as the difference between standard and deviant tones is increased, the latency of the MMN decreases while that of the N1 is maintained; in our Experiment 1 the magnitude of pitch deviance had a significant effect on the latency of the response, irrespective of the regularity of the sequence, once again more compatible with the properties of the MMN than the N1. Finally, as declared by Picton et al. (2000), the intracerebral origins of the two processes are distinct; the negativity of the present study had a scalp distribution which was consistently maximal at Fz, whereas the CN1 was usually larger at Cz (Jones et al., 1998, 2000; Jones and Perez, 2001). These arguments were presented in a previous paper (Hung et al., 2001), describing a similar negative/positive complex to change in the pitch interval of a tone alternating between two pitches at 16 changes/s.

Other workers have established that an MMN can be evoked by various types of change in a repetitive sequence of two or more tones (e.g. Nordby et al., 1988; Schröger, 1994; Tervaniemi et al., 2001). Only a few studies, however, have employed a deviant tone outside the pitch range of the standard series (e.g. Schröger et al., 1992; Alho and Sinervo, 1997; Alain et al., 1998). The findings of the present study indicate that the amplitude of the MMN to a deviant tone of higher pitch is influenced by the regularity or randomness of the standard pattern (also probably by the degree of pitch deviance, although this did not quite reach significance in

Bonferroni-corrected *t* tests). Its latency, on the other hand, was only influenced by the degree of pitch deviance. In the second experiment, MMNs of similar amplitude were evoked by the first two successive deviants in a regular 16 note/s standard sequence, indicating that the mismatch process continues to operate on the sequence after one deviant has been detected, although no MMNs could be identified to deviants subsequent to the second. Under the optimal conditions of the present study (regular standard sequence, wide pitch deviance) the MMN measured 7.3 μV on average – markedly larger than the conventional response obtained with the oddball method and sine-wave tones, suggesting that the use of continuous, spectrally complex tones in rapid sequences may facilitate practical applications of the MMN in the assessment of higher auditory processes.

The MMNs recorded to changing the frequency of one tone in a repeating pattern of 8 (Schröger et al., 1992) or 9 different sinusoidal tones (Alho and Sinervo, 1997), suggest to the former authors that 'the spectro-temporal features of complex sound patterns are automatically and precisely represented in passive auditory sensory memory'. During continuous presentation of a 5-tone pattern, the exchange of two tones also produced an MMN (Schröger et al., 1994). The authors concluded that the MMN mechanism is not necessarily timed by an 'external' reference (such as a silent period), but is able to use 'internal' units extracted from the repetitive structure. Alain et al. (1998) recorded MMNs with similar scalp topography to frequency- and time-deviant sounds in a continuously repeating 4-tone sequence. None of these studies, however, examined the effect of randomizing the sequence in order to eliminate its rhythmic nature. Our findings confirm that a repetitive temporal structure, such that a particular tone is expected at a particular time, increases the amplitude of the MMN but is not essential for its generation. Even pseudo-random (non-rhythmic) patterns may become the 'standard' against which tones of deviant pitch are compared, indicating that the MMN mechanism can operate on sound sequences in which the next expected pitch is only specified with a certain probability.

The larger MMN in the context of the regular standard pattern might be seen as the combination of two mismatch mechanisms – first the occurrence of a deviant tone outside an expected range of pitch values, and secondly the failure of a particular pitch to occur at a given time. The resulting response might be comparable with the MMN obtained with simultaneous changes in two or more features of the standard (Levanen et al., 1993; Schröger, 1995). The fact that an MMN is elicited by the sudden cessation of pitch changes in a pseudo-random sequence (Vaz Pato and Jones, 1999) indicates that the expectation that some unspecified change should occur *at a particular time* is a sufficient condition for the process to be engaged when it does not. There is no doubt that the MMN can be elicited by entirely predictable deviants (e.g. Scherg et al., 1989; Sussman et al., 1998), but surprisingly there seems to be no information in the literature as to what extent its elicitation depends on the predictability of the time that the next sound should occur.

The relationship between the latency of the MMN and the degree of pitch deviation, irrespective of the regularity of the standard pattern, reflects the general experience that the MMN latency is inversely related to the magnitude of the difference between the deviant stimulus and the standards (e.g. Sams et al., 1985). The fact that the MMN was much shorter in latency than is customary may possibly have resulted from the use of complex tones, as was found by Tervaniemi et al. (1993) comparing piano tones with sinusoids. In a study of the contribution of different frequency bands to the CN1 (Jones and Perez, 2001), the upper partials in sum were found to contribute more than the fundamental, and responses to frequency change of the upper partials were also 10–15 ms shorter in latency.

In the second experiment, increasing the number of successive deviants did not significantly affect the amplitude or latency of the MMN or MMP, presumably because these parameters were mainly determined by the first deviant tone. However, after subtraction of the response to a single deviant, an MMN to the second deviant was observed in the individual waveforms and was clearly reproduced in the group mean. This second negativity had a scalp distribution similar to that of the first, and was also similar in amplitude. Previous studies of successive deviants have mostly employed two different violations of the standard pattern, e.g. frequency/location (Schröger, 1995), frequency/duration (Czigler and Winkler, 1996), intensity/direction of frequency glide (Winkler et al., 1998), duration/frequency alternation (Winkler and Czigler, 1998), and frequency/intensity (Takegata and Morotomi, 1999). When successive deviants were separated by less than 200 ms, sequential MMNs could be obtained only when the deviations violated different types of regularity of the preceding auditory sequence, e.g. duration and frequency alternation (Winkler and Czigler, 1998; Sussman et al., 1999). These findings suggest a 'temporal window of integration', putatively linked to the duration of the 'short auditory store' and corresponding to the minimum perceived duration of very brief sounds and the period over which loudness integration and forward and backward recognition masking occur (Cowan, 1984; Winkler et al., 1993). Sussman et al. (1999) and Deacon et al. (2000) recorded MMNs to two consecutive frequency deviants, but only when the latter were separated by much longer intervals. It is difficult to reconcile our findings with a number of studies (e.g. Winkler and Näätänen, 1992; Tervaniemi et al., 1994; Yabe et al., 1997, 2001) in which tones with SOA of less than ca. 170 ms were apparently treated as a single unit by the mismatch process. It may be significant that in our study both the deviants and the standards that they replaced were of different pitch.

A curious finding in our study relates to the latency of the MMN to the second successive deviant, which was surprisingly short. With presentation at 16 tones/s, a difference of about 62.5 ms might have been expected, but the measured mean value of 45.8 ms, although not significantly different from 62.5 ms on account of the rather large standard deviation, was suggestively lower. This effect might be related to a phenomenon described by Czigler and Winkler (1996). When they delivered stimuli deviating in both frequency and duration from a uniform sequence of tones, they obtained a single MMN, with latency related to the first deviant feature (frequency), but with larger amplitude than the MMN obtained for frequency deviants alone. It was proposed that when the two deviant features were consistently associated, as in the present study, the second might be anticipated. However, although the MMNs to consecutive deviants in the present study overlapped in time, their peaks could still be clearly distinguished by waveform subtraction in every individual.

Winkler et al. (1996) suggested that the main function of the MMN process may consist in the adjustment of a neural model of the auditory input. The regularities and irregularities of the stimuli are detected and the model is constantly upgraded in order to avoid unnecessary activation of the attentional system. Our study suggests that the MMN may have a further significance. A process which is sensitive to the temporal structure of continuous sound patterns and is capable of responding to sequential changes separated by less than 100 ms might be employed for the analysis of rapid repetitive and non-repetitive sound patterns, including those of music and speech. In contradistinction to the background function proposed by Winkler et al. (1996), therefore, we propose that the mismatch process may represent an early, pre-attentive stage in the sequential analysis of sound for information.

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