

# The Effects of Channel-Selective Attention on the Mismatch Negativity Wave Elicited by Deviant Tones

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## ABSTRACT

The mismatch negativity (MMN) is an event-related brain potential elicited by infrequent, physically deviant sounds in a sequence of repetitive auditory stimuli. Two dichotic listening experiments that were designed to optimize the selective focusing of attention provided a strong test of Näätänen's proposal that the MMN is unaffected by attention and reflects the operation of a strongly automatic mismatch detection system. In Experiment 1, tones were presented at intervals of 120–320 ms, and the deviant tones (intensity decrements) in both the attended and unattended ears elicited negative waves consistent in waveshape, latency, and distribution with previously described MMNs. In contrast to previous reports, however, the MMN elicited by the unattended-channel deviant was markedly reduced (peak amplitude of less than 1  $\mu\text{V}$ ) relative to the corresponding negative wave elicited by the attended-channel deviants (3–4  $\mu\text{V}$ ), as well as relative to previously reported MMNs (3–6  $\mu\text{V}$ ) elicited by comparable deviations in stimulus intensity. In Experiment 2, which employed interstimulus intervals of 65–205 ms, the unattended-channel MMN elicited by the deviant fainter tones was barely discernible, whereas the corresponding attended-channel negativity was again about 3–4  $\mu\text{V}$ .

These findings call into question the assertion that the auditory mismatch detection process and the associated MMN wave are wholly independent of attentional influence. Rather, these data provide evidence that the processing of stimuli in unattended channels can be attenuated or gated at an early sensory level under conditions of highly focused auditory selective attention.

**DESCRIPTORS:** Mismatch negativity, Event-related potentials, Selective attention.

Physically deviant stimuli in a repetitive train of sounds elicit a distinctive set of components of the auditory event-related potential (ERP). Several initial studies (Squires, Squires, & Hillyard, 1975; Ford, Roth, & Kopell, 1976; Snyder & Hillyard, 1976; Squires, Donchin, Herning, & McCarthy, 1977) reported that changes in pitch or intensity in a sequence of tones elicited a fronto-central N2 wave (160–200 ms) followed by a positive deflec-

tion (P3a) at 240–280 ms even when the tones were not being attended (e.g., subjects reading). It was proposed that the N2-P3a complex of waves “reflects the operation of a mismatch detector which signals any change in an ongoing background stimulus” (Snyder & Hillyard, 1976); these mismatch-specific waves were viewed as reflecting “a rather early stage of the mismatch-orienting response sequence” triggered by a deviant stimulus.

Subsequently, Näätänen and associates reported that this N2 wave could be subdivided into two separate components, an N2a or “mismatch negativity” (MMN) and an N2b (reviewed in Näätänen & Gaillard, 1983). These authors proposed that the MMN is unaffected by attention (Näätänen, Gaillard, & Mäntysalo, 1978, 1980; Sams, Alho, & Näätänen, 1984; Sams, Paavilainen, Alho, & Näätänen, 1985) and therefore reflects the operation of a strongly automatic mismatch detection process. In contrast, the somewhat longer-latency, more posteriorly-distributed N2b was said to be elicited in addition to the MMN in cases where attention is

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directed toward the stimuli; this N2b wave was considered to be intimately linked with a subsequent late positive (P3 or P300) wave (for reviews see Näätänen & Gaillard, 1983; Näätänen, 1986, 1988).

According to the proposals of Näätänen and associates, the MMN elicited by a deviant sound is not simply a consequence of its activating stimulus-specific neural elements (e.g., of the N1 component) that are in a less refractory state due to its infrequent occurrence (for a discussion, see Näätänen, 1985). In support of this proposal are observations that an MMN is elicited by intensity decrements as well as increments (Näätänen, 1986; see also Snyder & Hillyard, 1976)<sup>1</sup> and by both decreases and increases in duration (Näätänen, Paavilainen, & Reinikainen, 1989). An MMN-like wave has also been reported to occur when a constant interstimulus interval (ISI) is unexpectedly shortened (Ford & Hillyard, 1981; Nordby, Roth, & Pfefferbaum, 1988), a result that is difficult to explain in terms of activating less-refractory elements. The MMN is reportedly produced even when the deviations are very slight, at least for changes in pitch (Sams, Paavilainen, et al., 1985) and intensity (Näätänen, 1986). In general, it has been reported that the amplitude of the MMN is directly proportional to the magnitude of the stimulus deviation (up to a plateau at about 10% deviation), whereas its onset latency and duration have been reported to be inversely related to the degree of deviation (Näätänen, 1985).

Näätänen and associates have suggested that the sensitivity of the MMN to slight physical deviations together with its putative independence from attentional influence indicate that the physical features of auditory stimuli are fully analyzed even when the stimuli are unattended. According to this view (Näätänen, 1985, 1986), a template or neuronal trace is established by repetition of the standard stimuli, and the MMN is elicited when a deviant stimulus fails to match this trace. In order to accomplish this template-matching operation, it is postulated that the brain must have performed a "full analysis" of the physical features of both the standard and deviant stimuli (Näätänen, 1988). Re-

cordings of the magnetic counterpart to the MMN (Hari et al., 1984; Sams, Hämäläinen, et al., 1985) and dipole source localization of the electrical MMN (Scherg, Vajsar, & Picton, 1989) suggest that these analyses and comparison processes may take place in auditory cortex.

A key element of this interpretation of the MMN component is the claim that equivalent MMNs are elicited by attended and unattended deviant auditory stimuli. In previous studies that reported such equivalency (Näätänen et al., 1978, 1980; Sams et al., 1984), however, conditions were such that a strongly selective attentional set may not have been established. For example, in the dichotic listening experiments in which equivalent MMNs were reported (e.g., Näätänen et al., 1978, 1980), the stimuli were presented at relatively slow rates. As discussed previously (Schwent, Hillyard, & Galambos, 1976; Hansen & Hillyard, 1984; Woldorff & Hillyard, *in press*), slow stimulus presentation rates are generally not conducive to the selective focusing of attention during dichotic listening. In other experiments that reported attended and unattended MMNs to be equal (e.g., Sams et al., 1984), a single channel of stimuli was presented at fairly long interstimulus intervals while subjects either counted the deviants or read a book, conditions that also may not require highly focused attention.

The present study examined whether the MMN remains unaffected when conditions are optimized for the selective focusing of attention and the early selection of stimuli. Two dichotic listening experiments were carried out in which the attended tones were distinguished from the unattended tones by both ear of entry and pitch cues. The stimuli were presented very rapidly, and the target discrimination task within the attended ear was made rather difficult. The effects of attention on the ERPs elicited by the standard tones in these two experiments have been presented in other reports (Woldorff, Hansen, & Hillyard, 1987; Hackley, Woldorff, & Hillyard, 1987; Woldorff & Hillyard, *in press*) and will be only summarized here. Those data indicated that a highly selective focusing of attention had been induced that affected processing at an early level, in that: a) the ERPs were differentiated as a function of attention beginning at 20 ms after stimulus onset in the form of an enhanced positivity (the P20-50 wave) elicited by attended-ear stimuli; 2) the amplitude of the P20-50 attention effect was correlated across subjects with the amplitude of subsequent attention-related negativity known as the early Nd; 3) the early Nd had an onset latency of 60 ms and appeared to include an amplitude modulation of several of the exogenous subcomponents of the N1 wave; and 4) amplitude varia-

<sup>1</sup>Although an ERP change elicited by an intensity decrement is not as likely to be due to the activation of less-refractory neural elements as those elicited by, for example, a frequency deviation or an intensity increment, such an explanation cannot be entirely ruled out. For example, such a response could be the consequence of the activation of intensity-coding neural elements that respond selectively to the specific intensity of the fainter deviants and are therefore in a less-refractory state because those tones are less frequent.

tions of the ERP attention effects as a function of stimulus sequence were paralleled by sequential variations in the accuracy of the target discrimination performance. In addition, the prepulse inhibition of a brainstem-mediated auditory reflex (the post-auricular muscle reflex) was found to be modulated by this channel-selective attention (Hackley et al., 1987).

The present paper examines the ERPs to the deviant tones in these experiments. Because of the highly focused attentional state that was produced, these experiments provided a strong test of Näätänen's hypothesis that the MMN is independent of attentional influence. The principal questions of interest were whether an "automatic" MMN was elicited by the unattended deviant tones, and if so, whether it was equivalent to that elicited by the attended deviants. If the MMN can be suppressed or attenuated when attention is focused on another input channel, this would suggest that the physical features of unattended stimuli are not fully analyzed under such conditions and that auditory attention can modulate very early stages of processing.

## EXPERIMENT 1

### Methods

Sixteen well-trained subjects (aged 18–26, all female, 13 right-handed) listened through stereo headphones to sequences of short-duration (13 ms; 5-ms rise and fall times) tone pips randomly presented to the two ears (1500 Hz to the left ear, 2600 Hz to the right) at a rapid rate (interstimulus interval range 120–320 ms, rectangular distribution). The task was to listen selectively to one ear and detect occasional (9% per ear), difficult-to-detect deviant tones ("targets") of slightly lower intensity than the 55dB SL "standard" tones; target detections were registered by a right-hand button press. All the tones (both standards and deviants) in the other ear were to be ignored. The deviant tones were identical in waveshape to the standard tones in the same ear, differing only in intensity. The standard-deviant intensity difference was individually adjusted for each ear for each subject to achieve a level of target detectability of around 70–80 percent. This was to ensure that attention would have to be well-focused on the designated ear in order to perform the task, as well as to equate task difficulty between the two ears and across subjects. The intensity difference averaged 15dB and varied from 10–20dB across subjects and ear of stimulation.

Sixteen runs each of attend-left and attend-right conditions were presented in counterbalanced order. Runs in which the EEG was noisy, the task performance was poor, or subjects reported having lost their concentration, were deleted and re-done. Each run lasted approximately 95 seconds and consisted of 200 standards and 20 deviants delivered to each ear, giving

a total for each subject of 3200 attended standards, 3200 unattended standards, 320 attended deviants (targets), and 320 unattended deviants for each ear.

Brain electrical activity was recorded using Ag/AgCl electrodes placed at 11 scalp sites ( $F_{PZ}$ ,  $F_Z$ ,  $C_Z$ ,  $P_Z$ ,  $C_3$ ,  $C_4$ ,  $T_3$ ,  $T_4$ ,  $T_5$ ,  $T_6$ , and right mastoid) of the International 10-20 system, all referred to the left mastoid. The EEG was amplified with a bandpass of 0.1–100 Hz and digitized at 500/Hz channel onto magnetic tape. ERPs were averaged off-line (epoch length 1024 ms, prestimulus baseline 200 ms) and re-referenced to the algebraic average of the potentials at the two mastoids. Electro-ocular activity (EOG) was also recorded (from just below and to the left of the left eye) to enable artifact rejections of trials with blinks or other eye movements. A balanced sterno-vertebral placement referenced to the left mastoid was also recorded to enable later evaluation of evoked activity at the mastoids relative to this non-cephalic reference.

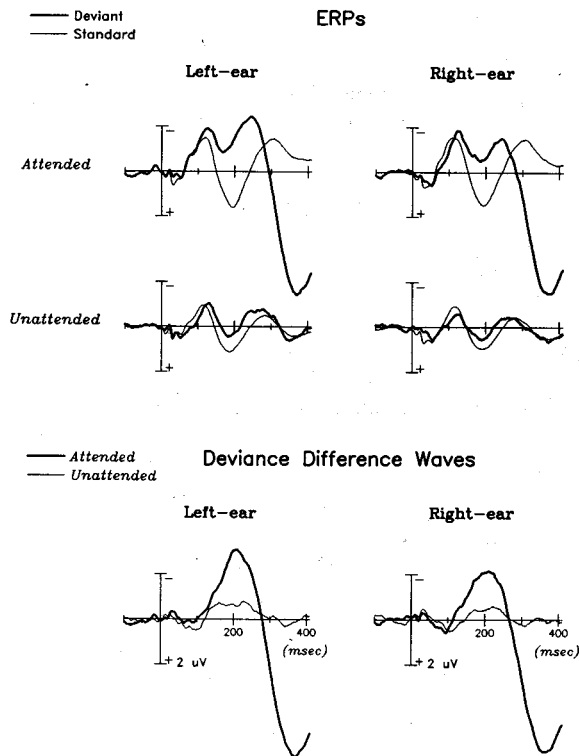
Averaged ERPs were obtained to both the standard tones and the deviant tones when attended and when unattended. Mean amplitudes of the ERP waveforms, relative to the prestimulus baseline, were measured separately across three 50-ms latency windows: A=100–150 ms, B=150–200 ms, and C=200–250 ms. For each window these values were entered into separate repeated-measures analyses of variance (ANOVAs). For midline sites, there were two factors, Attention (attended vs. unattended tones) and Deviance (deviant vs. standard tones). Lateral sites were analyzed in left-right pairs, so that an additional factor was Hemisphere of recording site. Also, to specifically test for the presence of an MMN in the unattended channel, additional ANOVAs analyzing the effects of Deviance were carried out on the unattended ERPs alone (in each of the three latency windows); a parallel set of analyses was also conducted on the attended ERPs alone.

In order to evaluate the deviance-related ERPs from Experiment 1 in more detail, difference waveforms were calculated for each subject by subtracting the ERPs to the standard tones from corresponding ERPs to the deviant tones for each of the attention conditions. Mean amplitudes of these waveforms were measured in the same three latency windows and entered into additional repeated-measures ANOVAs.<sup>2</sup>

### Results

Figure 1 shows the ERPs elicited at  $C_Z$  by the deviant tones when they were attended (first row) and unattended (second row), superimposed upon the ERPs to the corresponding standard tones. For both the attended- and unattended-ear tones, a negative deflection was evident in the deviant ERPs relative to the standard ERPs. This wave, which

<sup>2</sup>None of the ANOVAs in either experiment had more than two levels in any factor, and thus the Greenhouse-Geisser correction for heterogeneity of the variance/covariance matrix was not necessary for any of the analyses.



**Figure 1.** Top panel: Grand average ( $N=16$ ) ERPs from Experiment 1 elicited by the deviant and standard tones at the  $C_z$  site, shown for tones in left and right ears separately and as a function of direction of attention. Bottom panel: The corresponding attended and unattended "deviance difference waves" (deviant ERP minus standard ERP) for tones in each ear. Reference is the algebraic average of the two mastoids. Note that a deviance-related negativity was elicited in each of the attention conditions with similar onset latency, peak latency, and waveshape, but the attended one was considerably larger.

will be called here the "deviance-related negativity," began around 100 ms poststimulus and lasted until about 300 ms. For the attended tones, this deflection was considerably larger and was followed by a large P300 response.

The comparison between the ERPs elicited by the deviant versus standard tones can be seen more clearly in the difference waves calculated by subtracting the standard-tone ERP from the corresponding deviant-tone ERP (Figure 1, bottom row). The earliest components seen in these "deviance difference waves" included a small negativity peaking at around 35 ms and a small positivity peaking at around 100 ms for both attended and unattended channels. By referring back to the original ERPs, it can be seen that these early deflections were probably due to the direct effect of intensity on the early, exogenous ERP components; that is, the deviant

tones, because they were lower in intensity, evoked less positivity in the 20–50 ms range and less negativity in the N1 range (70–120 ms) than did the standard tones.

Following these small intensity-related effects, both the attended and unattended deviance difference waves at central sites showed distinct negative deflections that had similar waveshapes, onset latencies (ca. 100 ms), and peak latencies (ca. 200 ms). The amplitude of this deviance-related negativity, however, was approximately four times larger in response to attended-channel deviants than in response to unattended deviants. This amplitude difference between the attended and unattended negativities was evident at the very onset of the negative-going deflection (Figure 1, bottom).

The distributions of the deviance difference waves across all the scalp sites are shown in Figures 2 and 3 for the left- and right-ear tones, respectively. It can be seen that the deviance-related negativities were considerably larger for attended than for unattended tones at essentially all sites and that they shared a similar topographic distribution with a fronto-central maximum. The mean amplitude values of the attended and unattended difference waves at the midline sites  $F_z$ ,  $C_z$ , and  $P_z$  are shown in Figure 4 for Windows B (150–200 ms) and C (200–250 ms) separately, as well as averaged across these two windows.

The results of the statistical analyses of the deviant-tone and standard-tone ERPs at the various sites are listed in Table 1. The mean ERP amplitudes to the deviant tones measured across Window A (100–150 ms) were not significantly different from those to the standard tones at any of the sites except  $P_z$ , even though it appeared that the negative-going deflections in the deviance difference traces began at around 100 ms. This lack of a main effect for deviance seems likely to be due to the deviance-related negative difference being partially overlapped anteriorly by the preceding positive difference resulting from the above-mentioned intensity effect on the N1 wave. However, the observation that the attended deviance-related negativity rose faster and was larger than the unattended even in this earliest window was reflected in a significant Attention  $\times$  Deviance interaction at all central sites ( $C_3$ ,  $C_z$ ,  $C_4$ ) and at  $F_z$ .

In Window B (150–200 ms) and Window C (200–250 ms) the effects of deviance were highly significant at nearly all sites—the deviant ERPs were more negative than the standard ERPs. Only at  $F_{Pz}$  in Window C were the deviant ERPs not significantly more negative. The interaction of Attention  $\times$  Deviance was also significant at all sites in Windows B and C (except at  $F_{Pz}$  in Window C) because

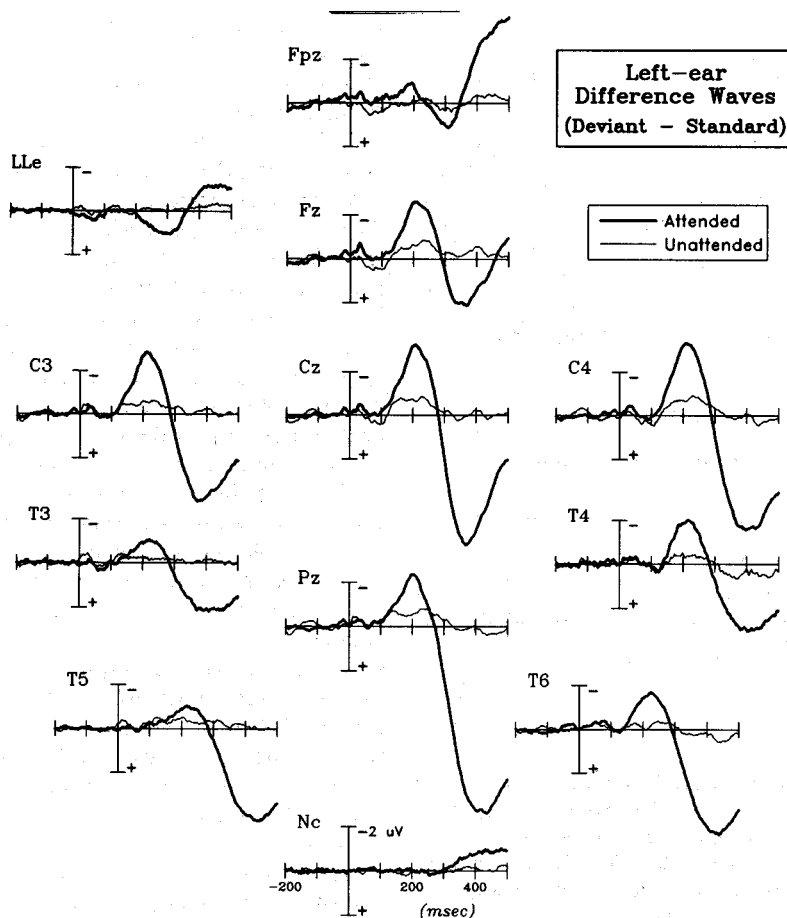


Figure 2. Distribution of the deviance difference waves across all the scalp sites in Experiment 1 for the left-ear tones. Reference for all sites was the algebraic average of the two mastoids. Nc=Non-cephalic (balanced sterno-vertebral). LLe=Lower Left eye (below and to the left of the left eye).

the deviance effect was considerably larger for attended-channel stimuli than for unattended-channel stimuli.

The results of the additional analyses testing whether the effect of deviance was significant for the attended and unattended ERPs considered separately are also listed in Table 1 (right columns). For Window A, as before, a decreased N1 elicited by the fainter deviant tones appeared to partially cancel out the increased negativity later in the window. Thus, in that window the effect of deviance was significant only at  $C_z$  and  $P_z$  and only for the attended responses. In Windows B and C, however, these analyses confirmed, for both the attended and unattended responses separately, that the deviants elicited significantly more negativity than the standards at almost all sites. The only cases where this did not hold were at  $F_z$  and  $F_{Pz}$  for unattended responses in Window B and at  $F_{Pz}$  for both attended and unattended responses in Window C.

Statistical analyses were also applied to the deviance difference waves in order to evaluate the interactions among the factors of Attention, Ear, and Hemisphere of recording at the lateral electrode sites (Table 2). In Window A, the deviance difference waves were significantly larger ipsilateral to the ear of stimulation at both central and temporal sites, which seems to be a likely consequence of the partially-cancelling N1 intensity effect tending to be larger contralaterally. In Windows B and C, on the other hand, the deviance difference waves were significantly larger contralateral to the ear of stimulation at the central sites ( $C_3$  and  $C_4$ ), as manifested by a significant Hemisphere  $\times$  Ear interaction (see Figures 2 and 3). The Hemisphere  $\times$  Ear  $\times$  Attention interaction was not significant for any of the lateral pairs.

The deviance difference waves at lateral central sites showed no significant main effects of hemisphere of recording nor any significant Hemisphere

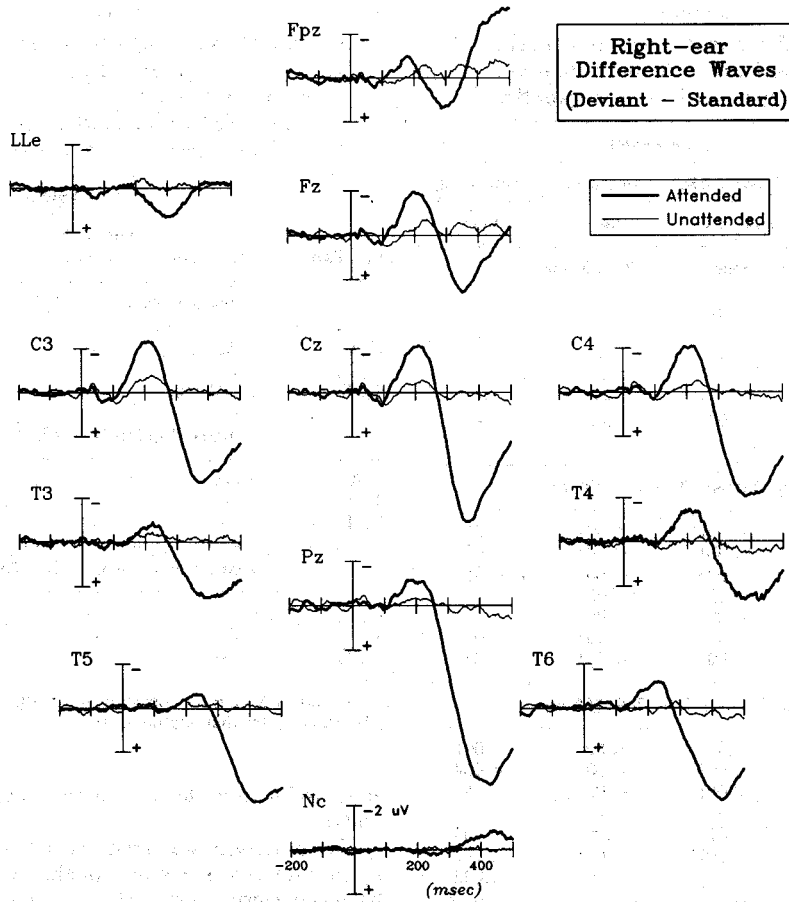


Figure 3. Same as Figure 3, for right-ear tones.

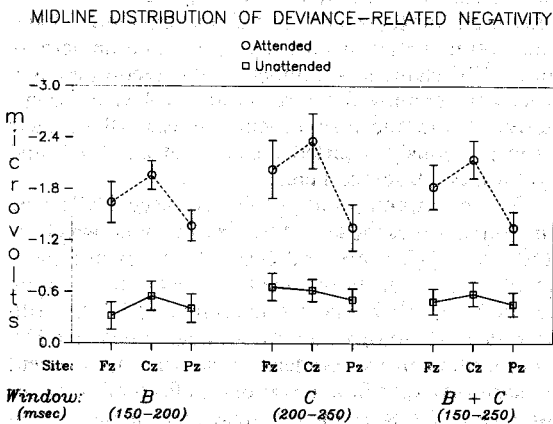


Figure 4. Mean amplitude values of the attended and unattended deviance-related negativities at the midline sites Fz, Cz, and Pz in Experiment 1, measured across Windows B and C separately as well as averaged across these two windows.

× Attention interactions in any of the measurement windows. However, there were significant effects of hemisphere at T<sub>3</sub>/T<sub>4</sub> and at T<sub>5</sub>/T<sub>6</sub> in Win-

dow A and at T<sub>3</sub>/T<sub>4</sub> in Window B, due to the larger amplitude of the deviance wave over the right hemisphere. In addition, in both Windows B and C, there were significant Hemisphere × Attention interactions for both lateral temporal pairs, resulting from the larger attended deviance-related negativity over the right hemisphere and a lack of such asymmetry for the unattended negativity.

EXPERIMENT 2

Methods

The second dichotic listening experiment was very similar to the first, with three main differences. First, because the parameters of this experiment were optimized for eliciting and recording the post-auricular reflex (Hackley et al., 1987), the standard-tone intensity was substantially louder (90dB SL), and subjects tensed their head and neck muscles by pulling against a weight on a pulley during all the runs. Second, the stimulus presentation rate was made even faster, with the interstimulus intervals ranging randomly from 65-205 ms (rectangular distribution). The aim was to facilitate further the selective focusing of attention by increasing both the information load and the rate of presentation

Table 1

EXPERIMENT 1: Significance levels of effects of deviance (Dev) and Attention  $\times$  Deviance (Attn  $\times$  Dev) on ERP mean amplitudes

Site	<i>p</i> Values			
	Att'd and Unatt'd ERPs		Att'd only	Unatt'd only
	Dev <sup>a</sup>	Attn $\times$ Dev <sup>b</sup>	Dev <sup>a</sup>	Dev <sup>a</sup>
Latency Window A = 100-150 ms				
C <sub>3</sub> /C <sub>4</sub>	—	<.04	—	—
T <sub>3</sub> /T <sub>4</sub>	—	—	—	—
T <sub>5</sub> /T <sub>6</sub>	—	—	—	—
F <sub>PZ</sub>	—	—	—	—
F <sub>Z</sub>	—	<.04	—	—
C <sub>Z</sub>	—	<.04	<.03	—
P <sub>Z</sub>	<.02	—	<.01	—
Latency Window B = 150-200 ms				
C <sub>3</sub> /C <sub>4</sub>	<.001	<.001	<.001	<.01
T <sub>3</sub> /T <sub>4</sub>	<.001	<.001	<.001	<.02
T <sub>5</sub> /T <sub>6</sub>	<.001	<.003	<.001	<.05
F <sub>PZ</sub>	<.05	<.03	<.02	—
F <sub>Z</sub>	<.001	<.001	<.001	—
C <sub>Z</sub>	<.001	<.001	<.001	<.01
P <sub>Z</sub>	<.001	<.001	<.001	<.03
Latency Window C = 200-250 ms				
C <sub>3</sub> /C <sub>4</sub>	<.001	<.001	<.001	<.001
T <sub>3</sub> /T <sub>4</sub>	<.001	<.001	<.001	<.004
T <sub>5</sub> /T <sub>6</sub>	<.001	<.001	<.001	<.05
F <sub>PZ</sub>	—	—	—	—
F <sub>Z</sub>	<.001	<.01	<.001	<.003
C <sub>Z</sub>	<.001	<.001	<.001	<.001
P <sub>Z</sub>	<.001	<.02	<.001	<.002

Note. Lateral sites (C<sub>3</sub>/C<sub>4</sub>, T<sub>3</sub>/T<sub>4</sub>, T<sub>5</sub>/T<sub>6</sub>) were analyzed as left-right pairs with Hemisphere as an additional factor.

<sup>a</sup> Where significant, the effect of deviance was always that the waveform of the deviant-tone ERP was more negative than that of the standard-tone ERP.

<sup>b</sup> Where significant, the effect of Attention  $\times$  Deviance was always that the deviant-related negativity was larger for the attended than the unattended ERPs.

of the channel-defining cues. Third, the stimuli from the stereo headphones were delivered to the two ears through air tubes (length 50 cm, diameter 2 cm) in order to mitigate electromagnetic stimulus artifacts. Stimulus duration was 10 ms, with rise and fall times of 1 ms.

Twelve subjects (aged 18-29, 9 female) participated in Experiment 2. For half the subjects, the left-ear tone pips were 2000 Hz and the right-ear stimuli were 6000 Hz; for the other half, the ear-pitch correspondence was reversed. The number of stimuli in a run was 360, resulting in a run length of approximately 50 seconds. There were 12 runs each in the attend-left and attend-right conditions. Deviant target tones were again decrements in intensity, averaging 20dB and ranging from 12-28dB across subjects and ear of stimulation. Six percent of the tones in each ear were deviants, resulting in a mean rate of occurrence similar to that in the first

Table 2

EXPERIMENT 1: Significance levels of effects of hemisphere of recording (Hem) and interactions of Hemisphere, Ear, and Attention (Attn) on mean amplitudes of deviant-minus-standard difference waves at lateral sites

Site Pair	<i>p</i> Values			
	Hem $\times$ Ear		Hem	Hem $\times$ Attn
	Hem $\times$ Ear	$\times$ Attn		
Latency Window A = 100-150 ms				
C <sub>3</sub> /C <sub>4</sub>	<.02 (i)	—	—	—
T <sub>3</sub> /T <sub>4</sub>	<.03 (i)	—	<.02	—
T <sub>5</sub> /T <sub>6</sub>	<.002 (i)	—	<.005	—
Latency Window B = 150-200 ms				
C <sub>3</sub> /C <sub>4</sub>	<.008	—	—	—
T <sub>3</sub> /T <sub>4</sub>	—	—	<.04	<.003
T <sub>5</sub> /T <sub>6</sub>	—	—	—	<.002
Latency Window C = 200-250 ms				
C <sub>3</sub> /C <sub>4</sub>	<.001	—	—	—
T <sub>3</sub> /T <sub>4</sub>	<.01	—	—	<.006
T <sub>5</sub> /T <sub>6</sub>	—	—	—	<.001

(i) indicates that the measures were larger (more negative) ipsilaterally rather than contralaterally.

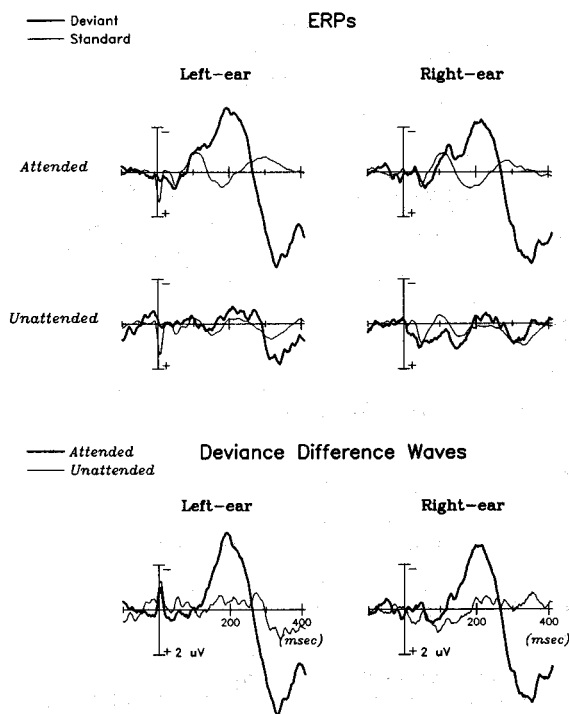
experiment (one deviant in each ear every 4-5 seconds).

Brain activity was recorded from the F<sub>Z</sub>, C<sub>Z</sub>, and P<sub>Z</sub> sites referred to a non-cephalic, potentiometrically-balanced sterno-vertebral placement. The EEG was amplified with a bandpass of 0.1-300 Hz and digitized at 500/Hz channel onto magnetic tape. ERPs were averaged off-line (epoch length 512 ms, prestimulus baseline 100 ms) after artifact rejection based on activity in an EOG channel. A number of other recording channels were employed for recording evoked myogenic activity from the post-auricular muscle; these have been previously reported (Hackley et al., 1987) and will not be presented here.

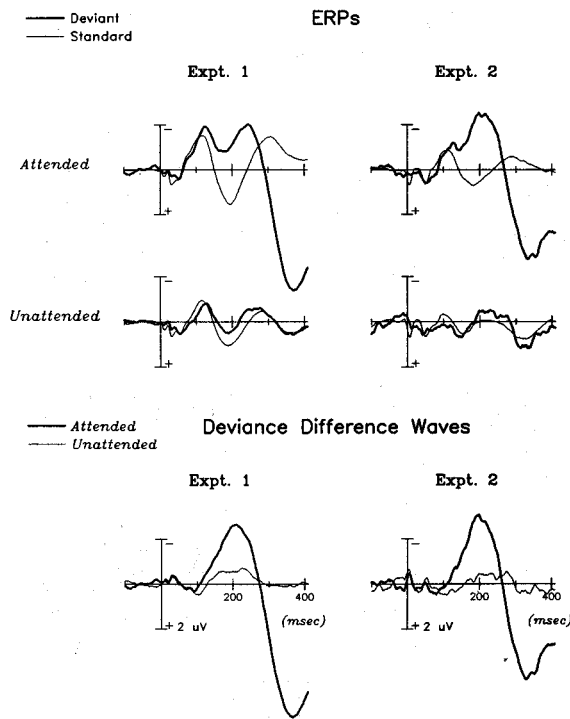
The mean amplitudes of the averaged ERPs were measured across the same three latency windows (100-150 ms, 150-200 ms, and 200-250 ms) as in Experiment 1. The values obtained for each window were entered into 2 $\times$ 2 repeated-measures ANOVAs, with factors of Attention (attended vs. unattended) and Deviance (deviant vs. standard). Also, as in Experiment 1, additional specific analyses of the effects of Deviance were carried out on the attended ERPs alone and on the unattended ERPs alone.

## Results

Figure 5 shows the vertex ERPs elicited by the deviant tones when they were attended (first row) and unattended (second row), superimposed upon the ERPs to the corresponding standard tones; below are shown the corresponding attended and un-



**Figure 5.** Top panel: Grand average (N=12) ERPs from Experiment 2 elicited by the deviant and standard tones at the  $C_z$  site, shown for tones in left and right ears separately and as a function of direction of attention. Bottom panel: The corresponding attended and unattended "deviance difference waves" (deviant ERP minus standard ERP). Reference was non-cephalic, consisting of a potentiometrically-balanced sterno-vertebral pair of leads.



**Figure 6.** Vertex ERPs and deviance difference waves from both Experiment 1 (left column) and Experiment 2 (right column), collapsed across ear of stimulation. Note that the attended deviance-related negativity was of similar amplitude in the two experiments, but the unattended negativity, which was small in Experiment 1, was reduced even further in Experiment 2.

attended deviance difference waves.<sup>3</sup> These vertex ERPs and difference waves are compared between Experiments 1 and 2 in Figure 6, with waveforms collapsed across ear of stimulation. As in the first experiment, the attended deviants elicited a negative deflection beginning at around 100 ms and peaking at around 200 ms, followed by a large, partially maximal P300 response. The unattended deviants in this second experiment, however, appear to have elicited very little of this negativity. Figure 7 shows the attended and unattended deviance difference waves for the three midline sites from Experiment 2, collapsed across ear of stimulation and

<sup>3</sup>The high degree of muscle tension in this second experiment, which was induced to facilitate the elicitation of the post-auricular reflex, resulted in the recorded ERPs having a large amount of high-frequency, background "noise" from myogenic sources. The waveforms in the figures for Experiment 2 have therefore been digitally smoothed (seven-point running average).

juxtaposed with the corresponding waveforms from Experiment 1.

As in Experiment 1, the mean amplitudes of the deviant ERPs measured across Window A (100–150 ms) were not significantly different from the standard-tone ERPs (Table 3); again, this was likely the result of partial cancellation from the direct intensity effect reducing the N1 in both the attended and unattended ERPs. However, an enlargement of the attended deviance-related negativity in this earliest window relative to the unattended response was reflected in a significant Attention  $\times$  Deviance interaction ( $p < .05$ ) at the  $F_z$  site.

In Window B the deviant-tone ERPs were significantly more negative than the standard-tone ERPs at all three sites. In Window C, this was true at  $C_z$  and  $P_z$ , but the effect did not reach significance at the  $F_z$  site. The Attention  $\times$  Deviance interaction was highly significant at all three sites in both Windows B and C.

The effect of deviance was also evaluated for the attended and unattended ERPs separately (Table 3, right two columns). For the attended ERPs in Win-



Deviance Difference Waves  
(Deviant ERP - Standard ERP)

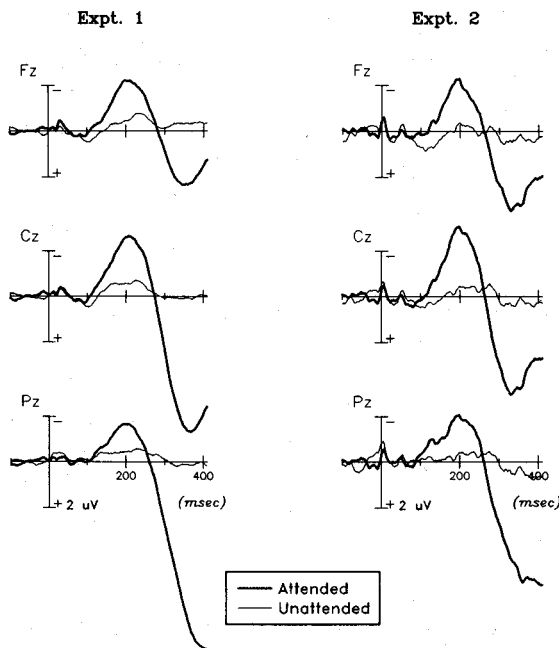


Figure 7. Midline distribution of the attended and unattended deviance difference waves from Experiment 1 (left column) and Experiment 2 (right column) for the three scalp sites ( $F_z$ ,  $C_z$ ,  $P_z$ ) that were common between the two experiments. Waveforms are collapsed across ear of stimulation.

Window A, this effect was significant only at  $P_z$  ( $p < .05$ ), presumably because at  $F_z$  and  $C_z$  there was partial cancellation of the negativity by the N1 intensity effect. For the unattended ERPs in this first window, the effect of deviance was significant only at the  $F_z$  site, wherein the deviant-tone ERP was significantly more positive than the standard-tone ERP, a result that seems likely due to the reduced size of the N1 component evoked by the fainter sounds.

In Windows B and C the ERPs elicited by the attended deviant tones were significantly more negative than the ERPs to the corresponding attended standard tones at all three sites. In sharp contrast, the effect of deviance on the unattended ERPs did not reach significance at any of the electrode sites for either of these two windows.

#### DISCUSSION

In both of the present experiments, the deviant tones in the attended channels elicited a prominent negative wave relative to the standards in the same channel that began at about 100 ms poststimulus

Table 3

EXPERIMENT 2: Significance levels of effects of deviance (Dev) and Attention  $\times$  Deviance (Attn  $\times$  Dev) on ERP mean amplitudes

Site	p Values			
	Att'd and Unatt'd ERPs		Att'd only	Unatt'd only
	Dev <sup>a</sup>	Attn $\times$ Dev <sup>b</sup>	Dev <sup>a</sup>	Dev <sup>a</sup>
Latency Window A = 100-150 ms				
$F_z$	—	<.05	—	<.02(+)
$C_z$	—	—	—	—
$P_z$	<.02	—	<.05	—
Latency Window B = 150-200 ms				
$F_z$	<.03	<.01	<.01	—
$C_z$	<.01	<.002	<.002	—
$P_z$	<.01	<.01	<.004	—
Latency Window C = 200-250 ms				
$F_z$	—	<.02	<.02	—
$C_z$	<.02	<.002	<.004	—
$P_z$	<.01	<.02	<.005	—

<sup>a</sup> Except where noted with a (+), significant effects of deviance were always that the waveform of the deviant-tone ERP was more negative than that of the standard-tone ERP.

<sup>b</sup> Where significant, the effect of Attention  $\times$  Deviance was always that the deviant-related negativity was larger for the attended than for the unattended ERPs.

and peaked at around 200 ms. The onset and peak latencies, waveshape, and distribution of these deviance-related negative waves were generally consistent with those described for the MMN wave reported in previous studies (for reviews, see Näätänen, 1985, 1986, 1988, 1990). In contrast to previous studies by Näätänen's group, however, the negativity elicited by the unattended deviant tones was considerably smaller than that elicited by the attended deviants, and, in the case of Experiment 2, the unattended deviants triggered no significant deviance-related negativity at all. These results strongly suggest that the MMN elicited by the deviants in the unattended channel was highly suppressed.

In the face of these results, it would appear difficult to maintain the view that the MMN is not influenced by attention. To do so, one would have to argue that equal-amplitude MMN waves actually were elicited by attended and unattended deviants in the present experiments, and that all the additional negativity in the attended difference wave was comprised of a separate negative component, such as the N2b, which was associated with the task relevance of the attended-channel deviants. There are a number of problems with such an explanation, however. To begin with, the amplitude of the re-

residual negativity in the unattended channels, which would presumably represent the automatic MMN, amounted to less than one microvolt in Experiment 1 and did not rise above noise levels in Experiment 2. These values are markedly smaller than the 3–6  $\mu\text{V}$  amplitudes reported in previous studies for the unattended (and presumably automatic) MMN elicited by comparable, or even substantially smaller, deviations in stimulus intensity or other attributes (e.g., Näätänen, 1985, 1986). On the other hand, the negativity elicited by attended-channel deviants in both of the present experiments (3–4  $\mu\text{V}$ ) was comparable in amplitude to those previously reported values. Thus, on amplitude grounds alone, it would appear that the inter-channel difference in deviance-related negativity observed here is more consistent with a hypothesized suppression of an attention-sensitive MMN in the unattended channel rather than with an augmentation of an automatic MMN by the addition of N2b activity for the attended-channel deviants.

In several previous studies reporting equivalent attended and unattended MMNs, the waveforms did appear to include an additional negative component (termed N2b) in response to the attended deviants (see Näätänen & Gaillard, 1983; Sams, Paavilainen, et al., 1985). In those cases, the “automatic” MMN was defined as the negative wave that appeared in the deviance difference waveform for the unattended tones, and the N2b was identified as an additional negative deflection in the attended-channel difference waveform that began somewhat later than the MMN and had a more posterior scalp distribution. In the present data, however, no such distinguishing characteristics for a second negative component in the attended-channel difference waveform were evident. Moreover, in Experiment 1, the residual deviance-related negativity elicited in the unattended channel, although small, was of sufficient amplitude to permit comparison to the attended-channel negativity; not only did the attended and unattended negativities have similar fronto-central distributions and similar peak latencies, but the attended-channel wave began its negative-going deflection at the same time as (if not earlier than) the unattended-channel wave and was significantly larger than the unattended in the earliest latency window in which they appeared. If, as the Näätänen framework would seem to require, the large amount of additional negativity in the attended difference wave consisted predominantly of N2b activity, then one would expect such a wave to exhibit the aforementioned distributional and latency characteristics of N2b that distinguish

it from the MMN. In the absence of such distinguishing characteristics, it would be circular to assert that the MMN in the present experiments was not affected by attention and that the entire difference between the attended and unattended deviance-related negativities was actually due to the presence of a separate N2b component.<sup>4</sup>

Although the attended deviance-related negativity did not display the distinguishing characteristics previously proposed for the N2b, the detailed distributional data from Experiment 1 do, in fact, suggest one difference between the negativity elicited by attended versus unattended deviants. In particular, the attended negativity (latency 150–250 ms) at the temporal sites was enlarged over the right hemisphere regardless of the ear of stimulation, whereas the very small residual unattended negativity at these sites exhibited a tendency toward contralaterality with respect to the stimulated ear. It is significant to note, however, that a right hemispheric preponderance has recently been reported by Näätänen and associates to be a hallmark of the MMN itself (Paavilainen, Alho, Reinikainen,

<sup>4</sup>Another conceivable explanation for the additional negativity elicited by the attended deviants in the present study might be that it was some sort of motor-related negativity associated with the button press to the attended targets. This possibility seems rather unlikely, however, for the following reasons: 1) Most of the subjects (~85%) were right-handed and used their right hand for the button response. Given that the motor potential tends to be larger contralateral to the hand used, and especially so for right-handed subjects (Kutas & Donchin, 1974), such a negativity should have been larger over the left hemisphere, rather than over the right as was found here. 2) Motor preparation negativities are generally considerably smaller frontally than centrally (Kutas & Donchin, 1980), rather than only slightly smaller as found in the present study. 3) The differentiation between the attended and unattended negativities began at around 100 ms. Therefore, if the additional negativity were a motor potential, then on a number of trials the deviant stimulus in the attended channel would have had to be evaluated as a target rather than a standard, and the motor preparation begun for the contingent button press, all by 100 ms. Given that the task was relatively difficult, and the mean reaction times were over 500 ms in both experiments, this seems unlikely. Furthermore, it also seems implausible that the first ERP sign of target/standard discrimination would be a motor-related wave peaking over 300 ms before the reaction time, rather than a potential related to stimulus evaluation. 4) As with the “all-the-additional-negativity-is-N2b” explanation, one cannot explain why the unattended-channel negativity was so small (or nonexistent) by hypothesizing the superposition of an additional motor-related component on the attended-channel negativity.

Sams, & Näätänen, 1990, cited in Näätänen, 1990). Thus, the only feature of the attended deviance-related negativity in Experiment 1 that appeared to distinguish it from its small unattended counterpart was a feature that has in fact been attributed to the presumably automatic MMN. This further suggests that the MMN reported by Näätänen may in fact include neural activity that is dependent upon the subject's attention and can be suppressed under conditions of highly focused attention as in the present experiments.

Additional considerations underscore the need for a better operational distinction between the MMN and the N2b and for a clearer statement as to when an N2b is or is not elicited. For example, the proposal that the MMN is not affected by attention is predominantly based on studies in which the deviance-related negativities in the attended and unattended channels were essentially equivalent in latency, shape, and size (e.g., Näätänen et al., 1978, 1980; Sams et al., 1984), with little indication that a second negative component was elicited by the deviants in the attended channel. Nevertheless, the attended deviants in those studies, as in the present study, did elicit a P300 component following the deviance-related negativity whereas the unattended deviants did not. In the context of Näätänen's distinction between the attention-independent MMN and the attention-related N2b associated with the P300, however, it is difficult to understand why the negativities elicited by the attended and unattended deviants would be so similar. If it were true that the unattended deviance-related negativity in Näätänen's studies consisted entirely of an automatic MMN, then the finding that the attended deviance-related negativity was basically equivalent implies that it also consisted entirely of this same MMN. Such a line of reasoning would lead to the rather curious conclusion that essentially *no* N2b at all was elicited by task-relevant attended targets (that *did* elicit P300 waves). This would appear difficult to reconcile with a framework that specifies that N2b waves should be elicited by deviant tones when they are attended and task-relevant (Näätänen & Gaillard, 1983; Sams, Paavilainen, et al., 1985; Näätänen, 1988).

If it actually were the case that N2b's were not elicited in the above-described experiments, one might conclude that the subjects' attention must not have been very strongly focused on the to-be-attended channel, or at least not focused enough to produce N2b's to accompany the P300s that were elicited. On the other hand, if attention was not focused very *selectively* in those studies and if elicitation of an N2b requires only a minimal level of attentional allocation, another possibility would be

that an equivalent amount of N2b activity was elicited in response to *both* the attended and unattended deviants; such N2b activity may then have comprised all or part of both the attended-channel and unattended-channel negative waves that were interpreted as "automatic" MMNs. In any case, if attention actually was not very highly focused in those studies, it would seem that the independence of the MMN from attentional influences was not very strongly tested.

Moreover, in at least one previous study in which the data were interpreted as if the MMN (to pitch deviations) were unaffected by attention (Sams, Paavilainen, et al., 1985), closer inspection of the data suggests that attention may have indeed affected the MMN amplitude. In that study, the automatic MMN was defined by the unattended deviance-related negative wave, and the differences between it and the attended wave were attributed to an N2b, as distinguished by the above-mentioned characteristics (i.e., there appeared to be a longer-latency, more posteriorly distributed, second deflection). Close inspection of the ERPs presented in that paper (Figures 2 and 4), however, suggests that the deviance-related negativity was larger for attended than for unattended tones early in the MMN latency range, *before* the anterior/posterior distributional shift occurred. In another study (Mäntysalo & Näätänen, 1987), significant differences between the attended and unattended deviance-related negativities were reported in the early latency range (105 ms) of the MMN (see Table 3 and Figure 2 of that study, especially the data for the shortest interstimulus interval). Therefore, these data further suggest the possibility of a direct effect of attention on the MMN itself, even though the additional negativity in the attended wave was still attributed to N2b.

In the present experiments, given the very small amplitude of the unattended-channel MMN, it is important to consider whether factors other than attentional suppression could have played a role in its reduction. Based on previous studies, however, and according to the general framework postulated by Näätänen and colleagues (see Näätänen & Gaillard, 1983; Näätänen, 1985, 1986, 1988), the stimulus parameters of the present experiments should have been conducive to eliciting relatively large MMNs. In regard to the size of the stimulus deviations, for example, Näätänen (1986) reported that lesser decrements of intensity ( $\sim 10$ dB) than those used in the present study (Experiment 1:  $\sim 15$ dB; Experiment 2:  $\sim 20$ dB) yielded unattended MMNs of 5–6  $\mu$ V, and that much smaller, near-threshold decrements of intensity ( $\sim 3$ dB) yielded MMNs of around 3  $\mu$ V. Furthermore, the Näätänen

framework asserts that the MMN should be larger at shorter interstimulus intervals (ISIs), such as those used in the present experiments, because the sensory "template" for the repetitively-presented standard tone would be stronger; some evidence has in fact been reported in support of such an inverse relationship between MMN amplitude and ISI length (Mäntysalo & Näätänen, 1987; Näätänen, Paavilainen, Alho, Reinikainen, & Sams, 1987).<sup>5</sup>

An additional factor that might be considered to account for the small size of the unattended MMNs in the present study is that the ISIs were *too* short, such that the deviants occurred so frequently that the MMN generators became refractory. At the stimulus rates and percentage of deviants employed in the present experiments, however, the unattended deviants occurred at intervals of once every 5 seconds or so. Considering that some of the studies by Näätänen and colleagues that yielded large unattended MMNs had parameters such that the unattended deviants occurred at least this frequently (e.g., Sams, Paavilainen, et al., 1985; Näätänen, 1986) or even more so (Näätänen et al., 1987), this explanation also seems implausible. Thus, it would appear that a major cause of the reduced amplitudes of the unattended MMNs in the present study, relative to the corresponding deviance-related negative wave in the attended channel as well as relative to previously reported MMNs, is that they were highly suppressed as a result of attention being strongly focused on the other channel.

Future research is required to determine whether the effects of attention reported here upon the ERPs to intensity-shift deviants will generalize to other types of auditory stimulus deviations (in pitch, lo-

cation, etc.). However, if the MMN elicited by deviations in as basic an attribute as intensity can be suppressed in an unattended channel, then this suggests that the unattended stimuli were not fully analyzed under those conditions and supports the view that auditory feature analysis is not strongly automatic. Rather, the modulation of the MMN observed here suggests that the processes of auditory feature analysis and mismatch detection (and their electrophysiological index, the MMN) may be "weakly automatic," not requiring attention for their occurrence but subject to attenuation when attention is strongly focused on another input channel.

As a final point, the data from Experiment 1 address the issue of the modality specificity of the negativities elicited by deviant tones. The view that the MMN wave is modality specific, proposed by Näätänen and Gaillard (1983), has received support from magnetic recording studies suggesting primary auditory cortex as a possible source (Hari et al., 1984; Sams, Hämäläinen, et al., 1985). If the MMN is modality specific, one might expect it to show a contralateral predominance with monaural tones. The data from the present Experiment 1 did show such a contralateral predominance at central sites for the deviance-related negative waves (both attended and unattended), thereby supporting the view that these waves have modality specific properties.

In summary, the present results indicate that the fronto-central negative wave elicited by deviant sounds over the interval 100–250 ms can be strongly influenced by attention under certain conditions, such that its amplitude is greatly attenuated in the unattended channel. This contrasts with numerous reports of Näätänen's group that such a negativity is of equal amplitude whether elicited by attended or unattended deviant tones (reviewed in Näätänen, 1985, 1986, 1988). The present results therefore call into question the hypothesis that the mismatch detection process and the MMN wave that has been reported as its electrophysiological signature are strongly automatic and wholly independent of attentional influence. Accordingly, these data also question the assertion that the physical characteristics of stimuli are automatically fully analyzed even when the stimuli are unattended. To the contrary, these data provide evidence that one of the mechanisms that humans employ during highly focused selective listening is the attenuation or gating of processing in unattended channels at an early sensory level.

<sup>5</sup>Another factor that might possibly have contributed to the small amplitudes of the unattended MMNs in the present study was the use of a fairly wide ISI (interstimulus interval) range relative to the average ISI. It is conceivable that this variability in the ISIs disrupted the establishment of the standard-tone template, or that the fast rate and ample variability interacted in such a way that the "automatic" detection of stimulus deviance was impeded. Such an explanation would be consistent with the result that the discrimination task in the present study was rather difficult despite the moderately large degree of deviation of the targets. However, if ISI variability can so strongly affect the size of the MMN elicited by a simple deviation such as intensity, then this factor must be well incorporated into any theory that postulates that the MMN reflects the template-mismatch following a strongly automatic physical feature analysis.

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