

# Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials

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## Abstract

Auditory event-related brain potentials (ERPs) were recorded during auditory and visual selective attention tasks. Auditory stimuli consisted of frequent standard tones (1000 Hz) and infrequent deviant tones (1050 Hz and 1300 Hz) delivered randomly to the left and right ears. Visual stimuli were vertical line gratings randomly presented on a video monitor at mean intervals of 6 s. During auditory attention, the subject attended to the stimuli in a designated ear and responded to the 1300-Hz deviants occurring among the attended tones. During visual attention, the subject responded to the occasional visual stimuli. ERPs for tones delivered to the attended ear were negatively displaced relative to ERPs elicited by tones delivered to the unattended ear and to ERPs elicited by auditory stimuli during visual attention. This attention effect consisted of negative difference waves with early and late components. Mismatch negativities (MMNs) were elicited by 1300-Hz and 1050-Hz deviants irrespective of whether they occurred among attended or unattended tones. MMN amplitudes were unaffected by attention, supporting the proposal that the MMN is generated by an automatic cerebral discrimination process.

**Descriptors:** Auditory, Cortex, Visual, Selective attention, Dichotic listening, Mismatch negativity, Intermodal

Selectively attended auditory stimuli, differing from unattended stimuli in location or pitch, elicit an event-related brain potential (ERP) that is negatively displaced in relation to an ERP elicited by identical unattended stimuli (Näätänen, 1990, 1992; Woods, 1990). This negative displacement (Nd) consists of two portions. The early Nd (Nd<sub>e</sub>) is largest at the frontocentral scalp and reaches its maximum between the latencies of the negative N1 (peak latency usually 80–120 ms) and positive P2 (peak latency 180–220 ms) deflections. The late Nd (Nd<sub>l</sub>) peaks at latencies longer than 300 ms and usually has a more frontal scalp distribution than the Nd<sub>e</sub>.

Näätänen (1982, 1990, 1992) has suggested that the Nd<sub>e</sub> is caused by an early component of an endogenous processing negativity (PN) generated by a stimulus selection process in the auditory cortex. According to Näätänen's theory, a matching process occurs between incoming stimuli and an *attentional trace*, an actively formed and maintained neuronal representation of the physical features (e.g., location or pitch) of the attended stim-

uli. This matching process occurs in the auditory cortex and generates the early PN. Even unattended stimuli may elicit some PN whose amplitude and duration varies with the resemblance of unattended and attended stimuli (Alho, Sams, Paavilainen, & Näätänen, 1986; Alho, Tottola, Reinikainen, Sams, & Näätänen, 1987; Michie, Bearpark, Crawford, & Glue, 1990; Michie, Solowij, Crawford, & Glue, 1993; Novak, Ritter, & Vaughan, 1992b). According to this theory, when attended and unattended auditory stimuli are physically close to each other, the Nd<sub>e</sub> represents the difference between a large PN elicited by attended stimuli and a smaller early PN elicited by unattended stimuli.

An alternative explanation is that the Nd<sub>e</sub> is caused by attentional enhancement of some exogenous N1 component or sub-components, especially in conditions where the attended and unattended stimuli are delivered at a very fast rate (Hillyard, Hink, Schwent, & Picton, 1973; Woldorff & Hillyard, 1991). We recently obtained evidence for attention-related modulation of the rising phase of the N1 in an experiment in which subjects attended to the conjunction of tone frequency and location (Woods, Alho, & Algazi, 1994). The rising phase of the N1 arises from a generator that is tonotopically organized (Woods, Alho, & Algazi, 1993): high frequency tones elicit a frontal negativity and a simultaneous posterior temporal positivity (N1/P90), and low frequency tones elicit a central negativity without accompanying positivity. When high frequency tones are presented in the ear to which the subject is attending, the N1 and the P90 are both enhanced in amplitude (Woods et al., 1994). No correspondingly enhanced positivity is noted for lower frequency tones, which suggests that a portion of the early Nd<sub>e</sub> may con-

This research was supported by grants from the NIDCD and the Veterans Administration Research Service to D. L. Woods and by a U.S. Public Health Service International Research Fellowship (FO5 TW04283) to K. Alho who was also supported by the Academy of Finland.

The constructive comments of Claude Alain, Risto Näätänen, and Robert Knight during the preparation of this report are acknowledged.

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sist of contributions from tonotopically organized exogenous ERP generators (see also Alcaini, Giard, & Perrin, 1992). However, even in such conditions, the peak of the  $N_d$  does not show a tonotopic dependency (Woods, Algazi, & Alho, 1991) and appears to receive a major contribution from the PN (Alho, 1992; Näätänen, Teder, Alho, & Lavikainen, 1992; Teder, Alho, Reinikainen, & Näätänen, 1993).

The  $N_d$  is caused by a later PN component elicited by attended stimuli (Näätänen, 1982, 1990), which may be generated in the frontal cortex (Giard, Perrin, Pernier, & Peronnet, 1988). The  $N_d$  may be associated with the maintenance and rehearsal of the attentional trace, with further processing of the attended stimuli, or with an arousal response following the occurrence of an attended stimulus (Näätänen, 1990; Näätänen & Michie, 1979; Näätänen & Picton, 1987).

Different attentional processes may contribute to the  $N_d$  elicited during intramodal selective attention discussed above and to the  $N_d$  elicited during intermodal selective attention (Alho, Woods, Algazi, & Näätänen, 1992; Hackley, Woldorff, & Hillyard, 1990; Woods, Alho, & Algazi, 1992; Woods et al., 1993; for a review, see Alho, 1992). The  $N_d$  elicited by attended auditory stimuli during intermodal (auditory-visual) selective attention appears to have a more posterior scalp distribution than the  $N_d$  elicited during intramodal selective attention (Woods et al., 1992). Furthermore, in intermodal conditions, the  $N_d$  is followed by a positive enhancement (Pd) of the ERP to the attended auditory stimuli (Alho et al., 1992; Hackley et al., 1990; Woods et al., 1992).  $N_d$  deflections are attenuated or absent in intermodal studies. Perhaps the frontal control processes of attention, which may contribute to the  $N_d$ , have a more important role in intramodal selective attention than in intermodal selective attention, where less precise stimulus selection is needed.

ERPs may also provide information on the analysis of unattended stimuli. First, during auditory intramodal selective attention, the active rejection of unattended stimuli (Alain & Woods, 1993; Woods, 1990) may generate a positivity (Alain & Woods, in press; Alho et al., 1987; Berman, Heilweil, Ritter, & Rosen, 1989; Donald, 1987; Michie et al., 1990; Näätänen, Gaillard, & Varey, 1981; Novak, Ritter, & Vaughan, 1992a).

Second, physically deviant stimuli in a sequence of auditory standard stimuli elicit a mismatch negativity (MMN) component, even during attention to other auditory or visual stimuli (e.g., Alho, Sams, Paavilainen, Reinikainen, & Näätänen, 1989; Alho et al., 1992; Näätänen, Gaillard, & Mantysalo, 1978; Sams, Paavilainen, Alho, & Näätänen, 1985; Woods et al., 1992). The MMN has been suggested to reflect automatic processing of stimulus features (e.g., Näätänen, 1990, 1992). However, MMNs elicited by small stimulus deviances (e.g., small intensity or frequency changes), but not those elicited by large deviances, may show some attentional modulation (Alho et al., 1992; Näätänen, 1991; Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993; Woldorff, Hackley, & Hillyard, 1991; Woods et al., 1992; for reviews, see Alho, 1992; Näätänen, 1992).

In the present study, intermodal and intramodal manipulations were combined. Sequences of tone bursts were presented dichotically as subjects attended either to the tones in the left or right ear or as they ignored the tones and attended to occasional visual stimuli. Thus, the effects of intramodal selective attention could be examined by comparing auditory ERPs elicited by attended and unattended tones during auditory attention conditions, and the effects of intermodal attention could be

examined by comparing auditory ERPs during attend auditory conditions and attend visual conditions. The fact that the current experiment resembled in many respects (e.g., attention tasks, interstimulus intervals) our previous experiments of intermodal selective attention (Alho et al., 1992; Woods et al., 1992) made it also possible to compare the present attention effects on ERPs with effects of intermodal selective attention observed in previous studies.

Furthermore, in the present study, the automaticity of stimulus change processing could be studied by comparing MMNs elicited by deviant stimuli occurring in unattended and attended auditory inputs. Both large and small stimulus changes were used because results from our previous studies on intermodal selective attention (Alho et al., 1992; Woods et al., 1992) have suggested that attention may modulate the MMN for slightly deviant stimuli (such as the 1050-Hz tones used in the current study) but not the MMN elicited by larger deviances.

## Methods

### Subjects

Fourteen right-handed subjects with normal hearing and normal corrected visual acuity participated in the experiment. Data from two subjects were discarded because of excessive electroencephalogram (EEG) artifacts caused by eye movements, blinks, or muscle activity. Of the remaining 12 subjects (ages 19–32 years, 4 women, 8 men), 10 had previously served as subjects in similar ERP studies. All subjects were paid students or laboratory personnel. Before participating, they gave informed consent according to guidelines of Veterans Administration Medical Center and University of California–Davis.

### Stimuli and Procedure

Auditory and visual stimuli were presented in randomized order in blocks of 880 stimuli. Interstimulus intervals (ISIs) varied randomly (rectangular distribution) between 200 and 400 ms in 20-ms increments.

Auditory stimuli were monaural sinusoidal tone bursts (75 dB sound pressure level [SPL], 50 ms duration with 5-ms rise and fall times) presented through TDH-39 headphones randomly to the subject's left or right ear over a continuous binaural broadband masking noise (60 dB SPL). Right- and left-ear standard tones of 1000 Hz occurred with probabilities of 37.5% each. In both ears, deviant tones of 1050 Hz and 1300 Hz were presented with 5% probabilities each.

The remaining 5% of stimuli were white vertical gratings on a black background (spatial frequency, two cycles/degree of visual angle; luminance, 6 foot-lamberts; contrast, .99; duration, 50 ms; size,  $3.9^\circ \times 3.9^\circ$ ). These stimuli appeared in the center of a television monitor subtending  $11.2^\circ \times 15.4^\circ$  and positioned in front of the subject at the distance of 150 cm.

There were three attention conditions: attend visual, attend right ear, and attend left ear. In each condition, a total of 12 stimulus blocks (10,560 stimuli) were presented. The order of the conditions was reversed for half of the subjects.

In the attend visual condition, the subject's task was to respond with a button press of the right thumb to all visual stimuli and to ignore the auditory stimuli. In the attend right ear and attend left ear conditions, the subject was instructed to respond to the 1300-Hz deviants in the designated ear and to ignore the auditory stimuli delivered to the opposite ear and the visual stimuli. In all three conditions, subjects were instructed to be both



fast and accurate in their responses. Furthermore, in all conditions, subjects were instructed to focus on a small fixation star attached to the center of the visual display. Fixation was assured in the beginning of each stimulus block, and the eye position was continuously monitored with vertical and horizontal electrooculogram (EOG) and with a closed-circuit video camera.

#### EEG Recording and Averaging

The EEG (bandpass 0.1–100 Hz) was continuously sampled (256 Hz/channel) from 27 scalp electrodes: Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, PA1 (left preauricular point), T1 (between F7 and T3), T3, C3, Cz, C4, T4, T2 (between F8 and T4), PA2 (right preauricular point), M1 (left mastoid), T5, P3, Pz, P4, T6, M2 (right mastoid), O1, Oz, and O2. To monitor the EOG changes, additional electrodes were attached below the left eye (BE) and lateral to the left eye (LE). In addition, one electrode was attached to the tip of the nose (NO). All electrodes were referenced to interconnected, electrocardiogram-balanced electrodes at the base of the neck (Woods & Clayworth, 1985).

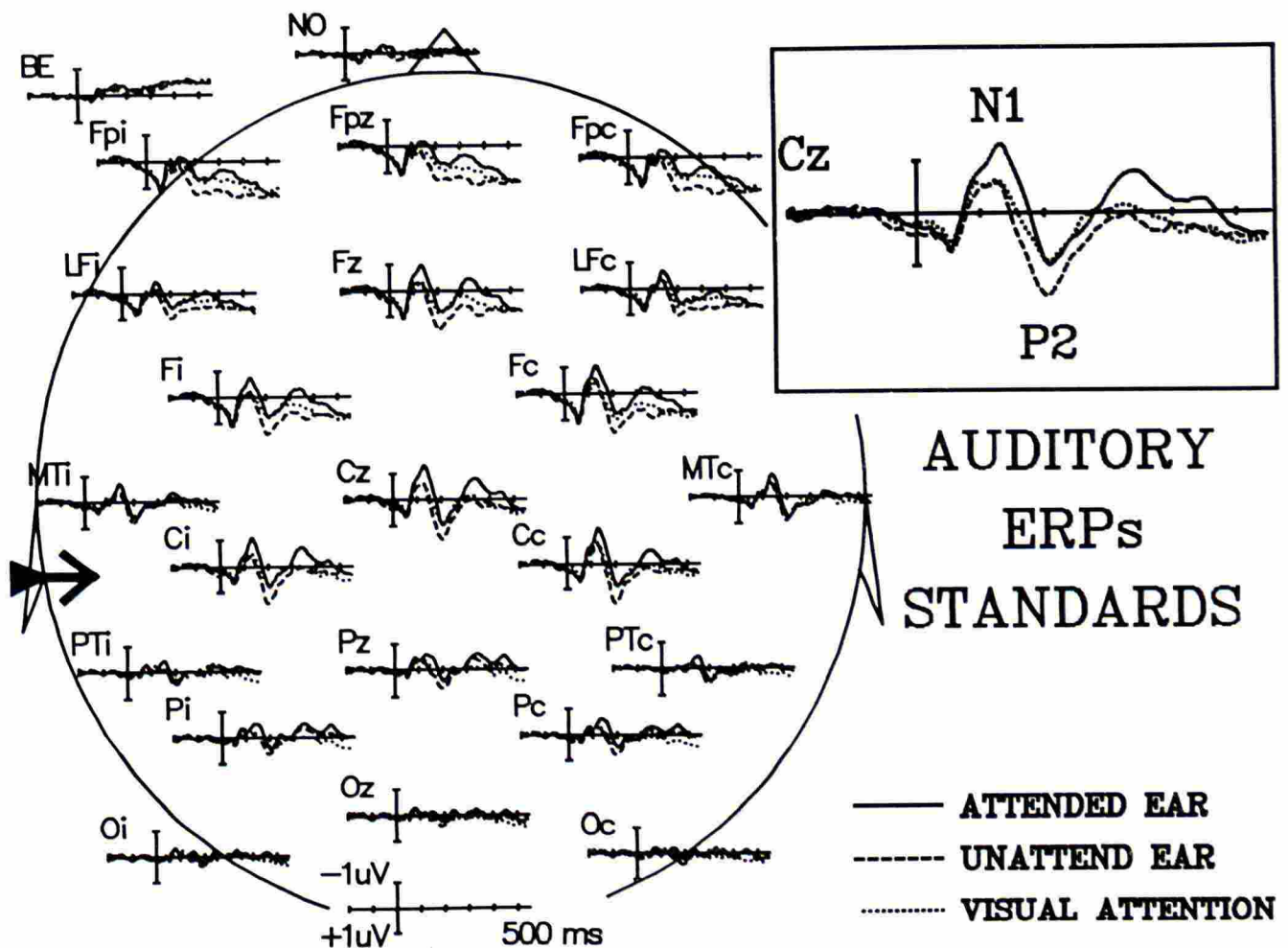
EEG epochs of 1,000 ms, including 200 ms of prestimulus activity, were averaged off-line by a computer. Trials contami-

nated by vertical or horizontal eye movements or blinks (peak-to-peak amplitude at Fpz, BE, or LE during an epoch exceeding 80  $\mu$ V), bursts of electromyogram activity, amplifier clipping, or other artifacts were automatically excluded from the averages. In each stimulus block, the epoch associated with the first stimulus was omitted. To avoid baseline contamination of auditory ERPs by large ERPs for occasional visual stimuli, ERPs for auditory stimuli occurring within 600 ms of visual stimuli were omitted from the average.

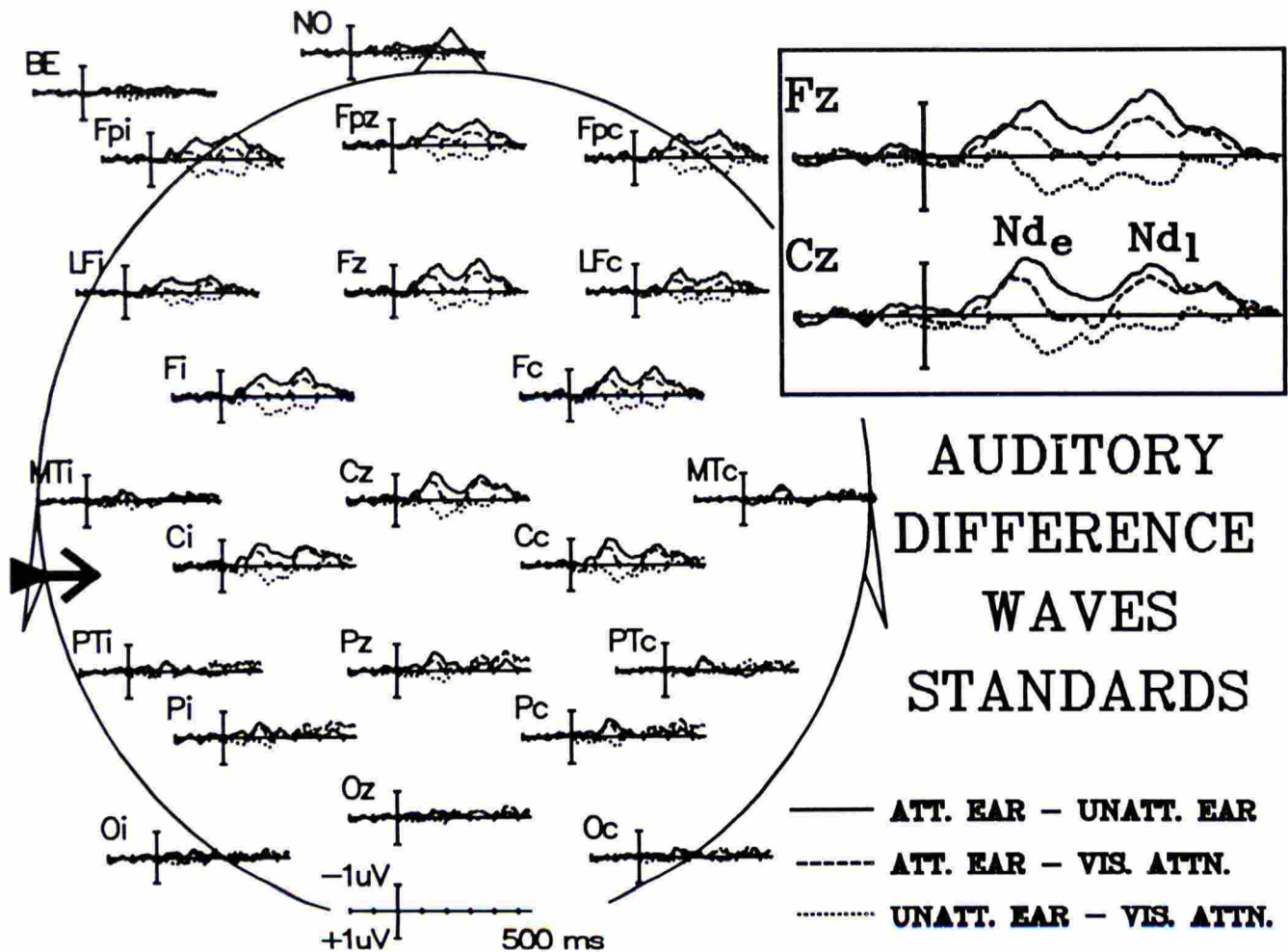
Only hit trials (a response following target onset within 80–1,000 ms) were included in ERPs for target stimuli, whereas ERPs for nontarget (1050 Hz) deviants occurring in the attended ear included only correctly rejected stimuli (no response within a 80–1,000-ms window following a nontarget).

#### Data Analysis

After averaging, ERPs were digitally filtered to eliminate frequencies above 40 Hz. ERP peak amplitudes and mean amplitudes over consecutive 20-ms intervals between 30 and 510 ms from stimulus onset were measured in reference to a 200-ms prestimulus baseline.



**Figure 1.** Grand average (12 subjects) ERPs for standard tones when attended (solid line) and when unattended during auditory (dashed line) and visual (dotted line) attention. ERPs were averaged across ear of stimulation and computationally transposed so that those on the left of the figure were ipsilateral to the stimulated ear (arrow). Electrodes have been relabeled accordingly (i = ipsilateral, c = contralateral). *Inset:* ERPs at Cz.



**Figure 2.** Difference waves showing the effects of selective attention. Solid lines are ERPs for attended standard tones minus ERPs to unattended standard tones during auditory attention. Dashed lines are ERPs for attended standard tones minus ERPs for standard tones during visual attention. Dotted lines are ERPs for unattended standard tones during auditory attention minus ERPs for standard tones during visual attention. *Inset:* Enlarged difference waves at Fz and Cz.

Behavioral performance was scored by a computer. Correct responses occurring from 80 to 1,000 ms after a target onset were defined as hits, and mean hit reaction times (RTs) were calculated in each condition. Also, the percentages of detected targets and false alarms were determined. Responses outside the 80–1,000-ms response were defined as false alarms.<sup>1</sup>

The ERP and performance data were statistically evaluated with an analysis of variance for repeated measures. Significance levels were adjusted with the Greenhouse–Geisser correction when appropriate. However, the original degrees of freedom are reported for each analysis. Although the epsilon values are not provided, almost all comparisons that are shown as significant

would remain significant even if the most conservative degrees of freedom were adopted.

## Results

### Performance

In attend right ear and attend left ear conditions, the percentages of detected 1300-Hz target stimuli were 84.2% ( $SD = 9.0\%$ ) and 85.5% ( $SD = 7.4\%$ ), respectively, and the percentages of false alarms were 10.1% ( $SD = 5.5\%$ ) and 10.3% ( $SD = 6.8\%$ ), respectively. Mean reaction time to the right-ear target stimuli was 431 ms ( $SD = 39$  ms) and to the left-ear target stimuli was 436 ms ( $SD = 54$  ms). RTs were shorter when a target tone was immediately preceded by a tone in the same ear ( $M = 416$  ms,  $SD = 41$  ms) than when preceded by a tone in the unattended ear ( $M = 449$  ms,  $SD = 53.5$  ms;  $F[1,11] = 43.55$ ,  $p < .01$ ; cf. Woods, 1990; Woods et al., 1994).

In the attend visual condition, all visual stimuli were targets. Mean RT to visual stimuli was 338 ms ( $SD = 50$  ms), and 97.1% of visual stimuli were correctly detected. Only 5.7% of responses

<sup>1</sup>The  $d'$  values were not calculated for two reasons. First, the variations in the sensory distributions were unequal for target and nontarget stimuli, because in each condition there was only one target stimulus but there were six nontargets. Second, the number of false alarms was small relative to the number of nontarget stimuli. Therefore, the  $d'$  values would have mainly reflected the percentages of correctly detected targets.



were given outside the response window (80–1,000 ms after a visual stimulus).

### ERPs for Standard Tones

Figure 1 shows ERPs for attended and unattended standard tones. Standard tones elicited N1 (mean peak amplitude and latency at Cz:  $-1.2 \mu\text{V}$  and 116 ms) and P2 deflections ( $1.3 \mu\text{V}$ , 206 ms) that were largest at central scalp sites. The N1 tended to be larger over the hemisphere contralateral to the stimulated ear (mean amplitudes at C3 and C4 over 110–130 ms for unattended standards: contra,  $-0.7 \mu\text{V}$ ; ipsi,  $-0.4 \mu\text{V}$ ), whereas the P2 was symmetrically distributed (190–210 ms: contra,  $1.1 \mu\text{V}$ ; ipsi,  $1.0 \mu\text{V}$ ).

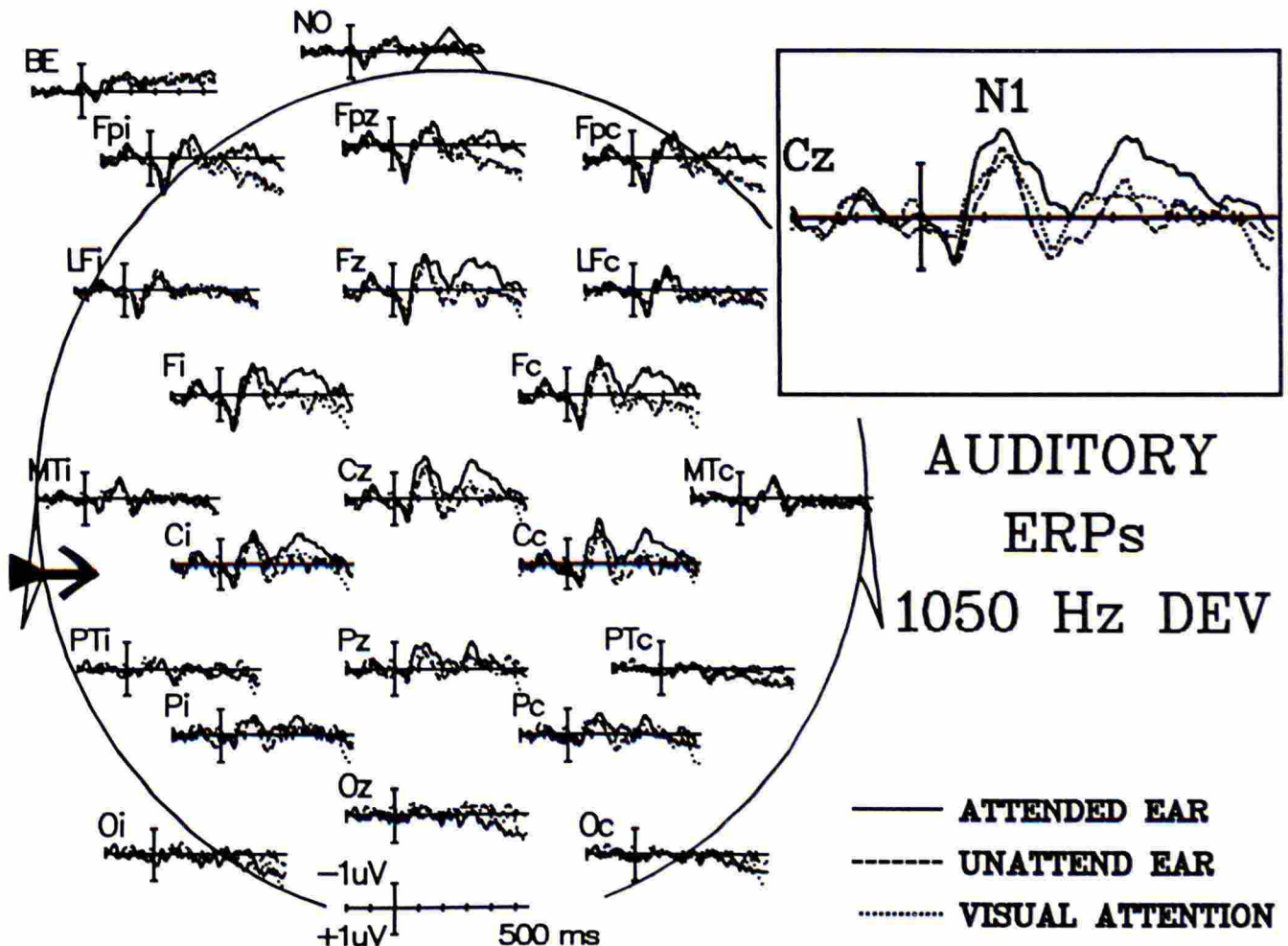
In auditory attention conditions, ERPs for standard tones in the attended ear showed a long-duration negative displacement in relation to ERPs elicited by standard tones delivered to the unattended ear (Figure 1). Analyses of variance for mean amplitudes at Cz over consecutive 20-ms periods showed significant effects over the latency range of 50–470 ms ( $F[1,11] = 5.70\text{--}52.70$ ,  $p < .05$  in all cases). This Nd had two peaks (Figure 2, solid lines). The Nd<sub>c</sub> had maximal amplitudes at Cz at 150–170 ms and was somewhat larger over the hemisphere con-

tralateral to the stimulated ear (e.g., C3/C4, 150–170 ms: contra,  $-1.0 \mu\text{V}$ ; ipsi,  $-0.8 \mu\text{V}$ ). The Nd<sub>i</sub> was largest at Fz at 330–370 ms and was symmetrically distributed.

A comparison of the ERPs for attended standard tones with ERPs for standard tones during visual attention (Figure 2, dashed lines) indicated two consecutive but smaller Nds (Cz: 110–190 ms,  $F[1,11] = 5.60\text{--}20.59$ ; 290–490 ms,  $F[1,11] = 6.63\text{--}15.44$ ;  $p < .05$  in all cases). ERPs for standard tones delivered to the unattended ear during auditory attention were significantly more positive than ERPs for standard tones during visual attention (Figure 2, dotted lines; Cz, 150–290 ms,  $F[1,11] = 5.04\text{--}20.35$ ,  $p < .05$  in all cases). The early part of this positivity (130–230 ms) had similar maximum amplitudes at Fz and Cz, whereas the later part (230–300 ms) was largest at Fpz, Fz, and Cz.

### ERPs for Deviant Tones

Attention effects for 1050-Hz (nontarget) deviant tones resembled those observed for the standard tones (Figure 3). Although the effects of attention on standards and 1050-Hz deviants were significant over the latency range of 90–430 ms (at Cz,  $F[2,22] = 3.8\text{--}12.9$ ,  $p < .05$  for all comparisons), none of the interactions



**Figure 3.** Grand average ERPs for (nontarget) 1050-Hz deviant stimuli when presented to the attended (solid line) and unattended (dashed line) ear during auditory attention and when presented during visual attention (dotted line). ERPs were averaged across the left- and right-ear stimuli. *Inset:* ERPs at Cz.





1300-Hz deviants presented during visual attention showed an N1 followed by a small centrally distributed positivity (presumably a P3a).

The 1300-Hz tones elicited prominent MMNs in all conditions (Figure 6). Analyses of variance including tone type (standard, 1300-Hz deviant) and attention (attended ear, unattended ear, visual attention) variables for mean voltages indicated that ERPs for 1300-Hz deviants were significantly more negative than ERPs for standards at 70–150 ms ( $F[1,11] = 12.62$ – $30.74$ ,  $p < .01$  in all cases). At these latencies, no significant effects of attention on the MMN amplitude for 1300-Hz deviants were observed ( $F[2,22] = 0.27$ – $1.34$ ). For example, at 130–150 ms, mean MMN amplitudes averaged  $-2.0 \mu\text{V}$  for attended-ear deviants,  $-1.9 \mu\text{V}$  for unattended-ear deviants, and  $-2.0 \mu\text{V}$  during visual attention.

However, at longer latencies, differences between ERPs for 1300-Hz deviants in the three attention conditions were evident ( $F_z$ , 150–270 ms:  $F[2,22] = 8.43$ – $22.67$ ,  $p < .05$  in all cases). As seen in Figure 6, when the 1300-Hz deviants were targets, the MMN (peak at about 130 ms) was followed by a centrofrontally distributed N2b component. For 1300-Hz deviants delivered to the unattended ear, the MMN was followed by a frontally maximal sustained negativity lasting to 450–500 ms. During visual

attention, the MMN for 1300-Hz deviants was followed by a small positivity (P3a) and a subsequent frontal negativity.

### Visual ERPs

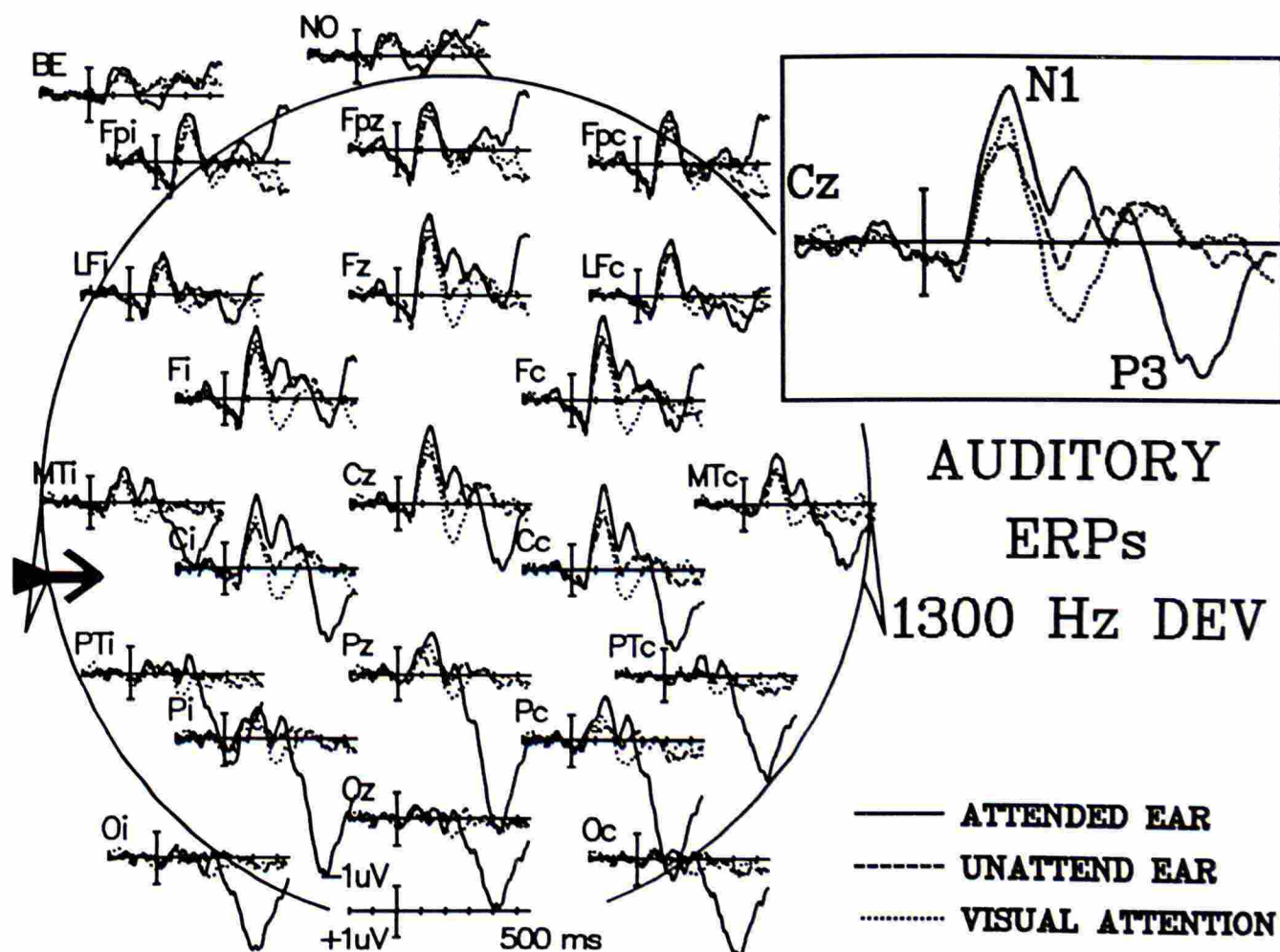
Visual ERPs (Figure 7) were most prominent at posterior scalp sites and included P120, N160, and P220 deflections resembling those elicited by foveal stimuli in our previous study (Alho et al., 1992). During visual attention (all visual stimuli were targets), these deflections were followed by a large P3 (mean peak amplitude and latency at Pz:  $11.5 \mu\text{V}$  and 333 ms).

Comparison of visual ERPs during visual attention and during auditory attention (Figure 7) showed significant enhancements of P120 (measured over 110–130 ms at O1, Oz, and O2;  $F[1,11] = 17.68$ ,  $p < .01$ ) and P220 (190–210 ms:  $F[1,11] = 5.09$ ,  $p < .05$ ; 210–230 ms:  $F[1,11] = 5.10$ ,  $p < .05$ ). The small enhancement of the N160 with visual attention failed to reach significance.

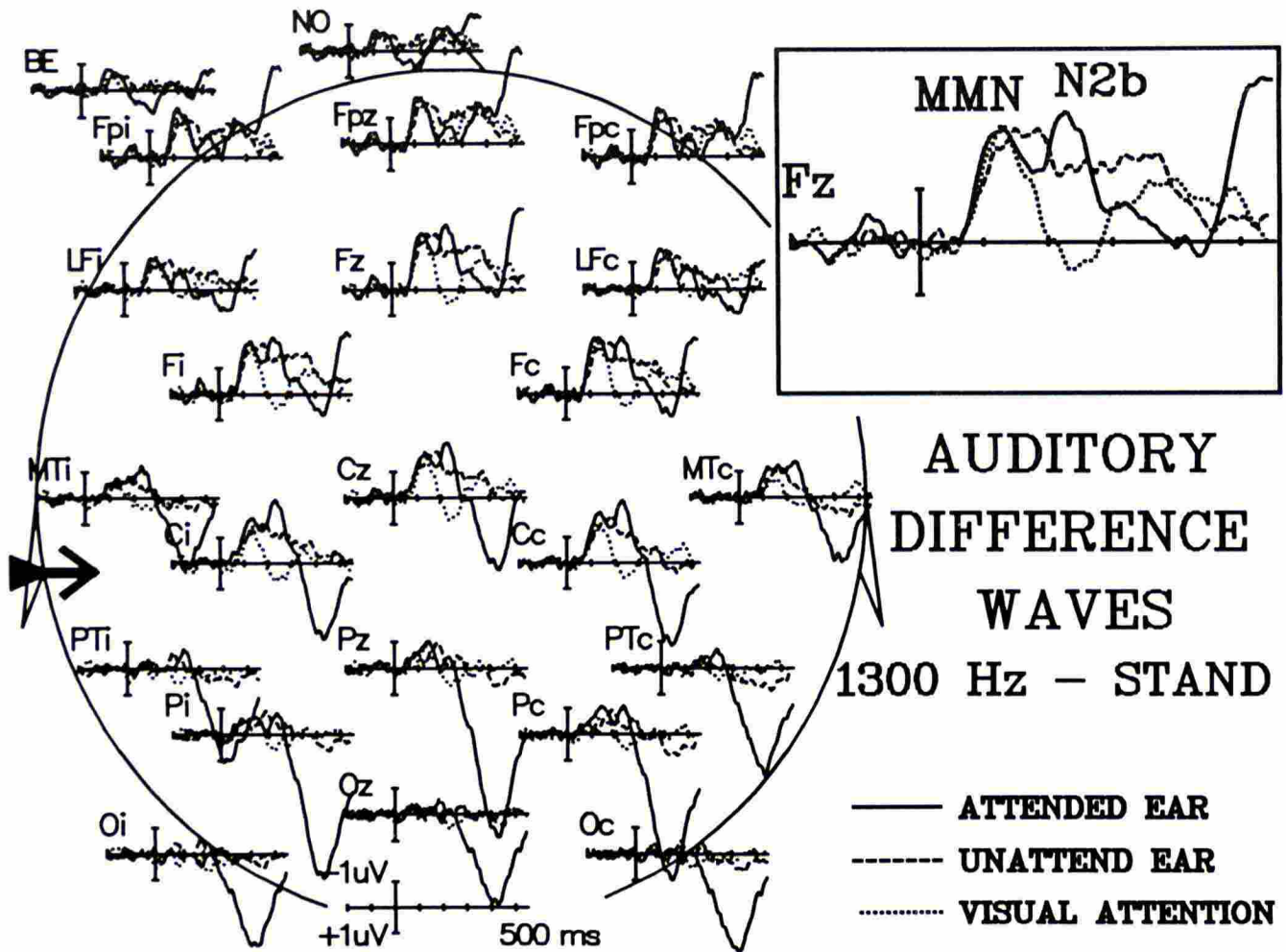
### Discussion

#### Effects of Attention on Auditory ERPs

ERPs for attended standard tones were negatively displaced in relation to ERPs elicited by standard tones during attention to



**Figure 5.** Grand average ERPs for 1300-Hz deviant tones occurring in the attended ear as targets (solid line), occurring in the unattended ear (dashed line), and occurring during visual attention (dotted line). ERPs were averaged across the left- and right-ear stimuli. *Inset:* ERPs at Cz.



**Figure 6.** Grand average difference waves obtained by subtracting ERPs for standard tones from ERPs for 1300-Hz deviant tones during visual attention (dotted line) and during auditory attention (solid line = targets; dashed line = unattended ear). Difference waves were averaged across the left- and right-ear stimuli. *Inset:* Difference waves at Fz.

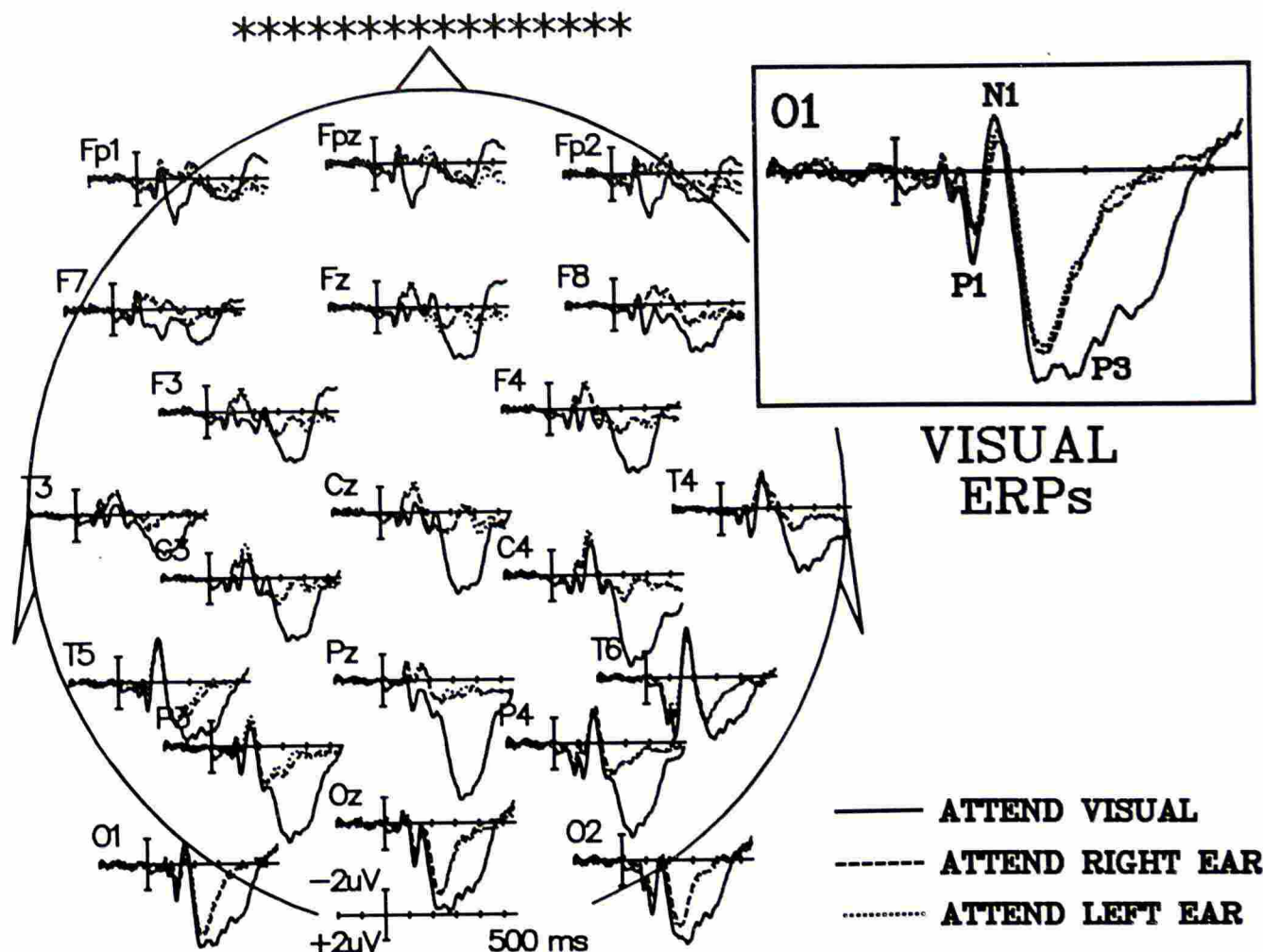
stimuli delivered to the opposite ear (Figure 2). This negative displacement consisted of early and late portions,  $Nd_e$  and  $Nd_l$ , respectively. The  $Nd_e$  had a longer duration, peaked considerably later, and had a more frontal scalp distribution than the  $N1$  elicited by unattended tones. These findings suggest that the  $Nd_e$  effect was caused by an early component of the endogenous processing negativity (PN; Näätänen, 1992) overlapping with the exogenous  $N1$  components (cf. Woods & Clayworth, 1987). As in previous studies, the  $Nd_l$  was more frontally distributed than the  $Nd_e$  (e.g., Hansen & Hillyard, 1980; Näätänen et al., 1981; Teder et al., 1993), which suggests that the  $Nd_l$  was caused by the later PN component presumably originating from frontal cortex (Giard et al., 1988; Näätänen, 1992).

Comparison of attended-ear ERPs with unattended-ear ERPs revealed larger  $Nd_e$ s and  $Nd_l$ s than comparison of attended-ear ERPs with auditory ERPs elicited during visual attention. This difference appears to be largely caused by enhanced positivity for unattended tones during attention to opposite-ear stimuli (Figure 2, dotted line, cf. Alain & Woods, in press; Alho et al., 1987; Berman et al., 1989; Michie et al., 1990; Novak et al., 1992a). This positivity commenced at about

130 ms from stimulus onset and lasted for several hundreds of milliseconds.

The positivity for unattended tones would contribute to the  $Nd_e$  and  $Nd_l$  observed in the attended – unattended difference waves obtained during auditory attention. This positivity might be associated with a rejection of unattended tones after they are found not to match with the attentional trace representing the spatial location of attended tones (cf. Alho et al., 1987). However, the positivity for unattended tones may have been caused by the termination of  $Nd_l$  elicited by preceding attended stimuli. During auditory attention, half of the unattended tones were preceded by attended tones eliciting large  $Nd_l$  deflections. The  $Nd_l$  had a duration of at least 500 ms (Figure 2). Because of the short ISIs (200–400 ms) used, it would overlap with ERPs elicited by subsequent stimuli. Therefore, the prestimulus baseline would include  $Nd_l$  activity for preceding attended tones. The termination of this  $Nd_l$  might have contributed to the broad positivity seen following unattended tones. It might have also reduced the negative displacement of ERPs for attended tones in relation to auditory ERPs during visual attention (Figure 2) because in the latter ERPs the positivity would not have been





**Figure 7.** Grand average ERPs for visual stimuli during visual attention (solid line; all visual stimuli were targets) and during auditory attention (dashed line = attend right ear; dotted line = attend left ear). *Inset:* ERPs at O1.

enhanced by a termination of  $Nd_1$ , which was not elicited by auditory stimuli during visual attention.

In intermodal (auditory-visual) selective attention experiments, the  $Nd_c$  elicited by the attended auditory stimuli is followed by a phasic  $Pd$  both when ISIs and attention tasks are similar to the present ones and when shorter ISIs and more difficult tasks are used (Alho et al., 1992; Hackley et al., 1990; Woods et al., 1992). However, in the present comparison of auditory ERPs elicited during auditory and visual attention, no  $Pd$  was observed. In the present experiment, auditory attention had an intramodal (attend to one ear or the other) and an intermodal component. Under these conditions, auditory ERPs appeared to be dominated by the effects of intramodal attention.

#### *Processing of Deviant Auditory Stimuli*

ERPs for 1050-Hz deviant tones showed a negative displacement with attention (Figure 3), suggesting that these tones elicited early and late PN components. Moreover, when these deviants occurred among unattended tones during auditory attention, they elicited a sustained positivity similar to that for attended standard tones. ERPs for 1300-Hz deviant tones were negatively displaced with attention (Figure 5), indicating that these tones also elicited an  $Nd_c$  when they were targets occurring among

the attended tones. The 1300-Hz targets also elicited an  $N2b$ , a  $P3$ , and a late frontal negativity associated with target detection (e.g., Näätänen, Simpson, & Loveless, 1982; Sams et al., 1985).

Both small and large pitch changes elicited frontally maximal MMNs revealed in difference waves obtained by subtracting standard-tone ERPs from deviant-tone ERPs (Figures 4 and 6). The MMN for small pitch changes was smaller in amplitude and longer in latency than the MMN for large pitch deviations (cf. Alho et al., 1992; Sams et al., 1985). In the deviant – standard difference waves for the 1300-Hz deviant tones (Figure 6), the negativity at the  $N1$  latencies may have been partly caused by the MMN and partly by a less refractory  $N1$  for the infrequent 1300-Hz deviant tones than for the frequent 1000-Hz standard tones (e.g., Butler, 1968; Lang et al., 1990; Scherg, Vajsar, & Picton, 1989; Woods, in press).

In our previous intermodal selective attention studies (Alho et al., 1992; Woods et al., 1992), auditory attention appeared to enhance MMNs for small frequency deviances occurring in an attended auditory stimulus sequence. However, in the present study attention had no significant effect on the MMN elicited by small frequency deviance. In most conditions of these previous studies, deviant stimuli were targets in attend auditory con-



ditions, whereas in the current experiment the small deviant stimuli were never targets, which suggests that part of the discrepancy in the effects of attention on the MMN may relate to the superimposition of target-specific negativities (e.g., the N2b and movement-related cortical potentials) in the MMN latency range.

No effects of attention on the MMN for 1300-Hz deviant tones were observed at latencies shorter than 150 ms (Figure 6). At longer latencies, attention effects did occur, but these would be expected because of the superposition of premotor potentials and the N2b on the MMN elicited by targets (Figure 6). In sum, when the MMN could be measured with relatively little contamination, attention appeared to have little effect on MMN amplitude for either small or large stimulus deviances. This result supports the proposal that the MMN is elicited by a largely automatic cerebral discrimination process (e.g., Näätänen, 1990, 1992).

In addition to the MMNs, the deviant – standard difference waves for 1050-Hz deviant tones included long-duration negativities in all conditions. An even larger sustained negativity was observed during auditory attention for the 1300-Hz deviant tones delivered to the unattended ear, and a late negativity was also elicited by 1300-Hz deviant tones during visual attention. All the sustained negativities for deviant tones had frontally dominant distributions. These negativities might be caused by long-duration MMNs. However, a recent MMN study on patients with frontal brain lesions (Alho, Woods, Algazi, Knight, & Näätänen, in press) indicated that under some conditions fron-

tal lesions are associated with attenuation of the MMN, although little effect on the sustained negativity is observed. This result suggests a different neural origin for the MMN and for the subsequent sustained negativity. Näätänen et al. (1982) observed a similar sustained negativity following the MMN for small pitch changes occurring among unattended auditory stimuli. They proposed that this negativity might reflect sensitization processes after an occurrence of a stimulus change, which elicits the MMN but does not trigger any subsequent endogenous processes. Such sensitization might be automatic preparation for detecting possible subsequent stimulus changes.

### *Effects of Attention on ERPs for Visual Stimuli*

In addition to large P3 deflections, ERPs for visual target stimuli showed early attention effects when compared with visual ERPs elicited during auditory attention. As in a previous study with similar foveal stimuli (Alho et al., 1992), the P120 and P220 deflections were larger at occipital scalp sites during visual attention than during auditory attention. Attention effects on visual ERPs were observed, although the visual stimuli occurred infrequently, on the average of once in 6 s. Thus, visual attention seems to be able to operate effectively at an early stage of cortical stimulus processing even when stimuli occur at relatively slow rates. This result implies that the visual attentional trace may last longer without sensory reinforcement than the attentional trace in the auditory modality (Alho, Lavikainen, Reinikainen, Sams, & Näätänen, 1990; Näätänen, 1990).

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(RECEIVED May 11, 1993; ACCEPTED November 8, 1993)

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