SELECTIVE ATTENTION AND THE AUDITORY VERTEX POTENTIAL

I: EFFECTS OF STIMULUS DELIVERY RATE[1]

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INTRODUCTION

In a noisy environment human listeners can readily focus their attention upon a single "channel" of auditory input and reject the information arising concurrently from competing sound sources. Perhaps the most striking demonstration of auditory selective attention is the dichotic listening paradigm (Cherry 1953; Moray 1959), wherein the contents of a spoken message presented to one ear are almost completely excluded from awareness while the listener's attention is directed towards a second spoken message in the other ear. Using the technique of computer averaging the scalp-recorded evoked potentials, it has become possible to investigate the neurophysiological mechanisms of selective attention in normal human subjects in dichotic listening situations and a host of other attentive tasks. Naatanen (1975) has recently made an extensive review of this area.

The scalp-recorded auditory evoked potential (EP) in man is recognized to consist of some 15 distinct waves (Picton et al. 1974), which reflect the transmission of auditory information through the nervous system from brainstem to cortex. Among the most prominent and consistent of these components are a negative wave (N_1) peaking at 80 to 130 msec after stimulus onset, and a positive wave (P_2) peaking at a latency of 160 to 200 msec (Davis et al. 1966). The N_1 and P_2 waves are also the earliest components to be altered reliably by changes in a subject's attentive state (Picton and Hillyard 1974).

Recent studies by Hillyard _et al_. (1973) and Schwent and Hillyard (1975) have reported highly significant enhancements of the auditory N_1 component with selective attention to one of two or more competing channels of tone pip stimuli presented in a random sequence to preclude "differential preparation" artifacts (Näätänen 1967; Karlin 1970). In these experiments it was shown that each channel of tones elicited substantially larger N_1s while being attended than when attention was directed to another channel. Two major design features were introduced in these studies which distinguish them from prior investigations that reported little or no attention-related lability for the N_1 wave (Näätänen 1967, expt. II; Hartley 1970; Smith _et al_. 1970; Karlin _et al_. 1970; Wilkinson and Lee 1972): the inter-stimulus intervals (ISIs) were shorter and/or the number of stimulus channels was larger than those used in the earlier studies. Both of these factors serve to increase the number of sensory events delivered per unit time (i.e. the "information load" on the subject). As suggested earlier by Hartley (1970) and Hillyard _et al_. (1973), a high density of auditory input may well be required if perception is to be selectively confined to one source; at lower rates of stimulation, subjects may find it difficult to avoid attending to all of the sensory channels. This supposition is consistent with behavioral studies showing that attention is not necessarily restricted to one channel when stimuli from multiple sources are delivered at relatively low rates (Lawson 1966; Shiffrin and Grantham 1974). In contrast, a high degree of selectively occurs with heavier processing loads such as trains of dichotic verbal stimuli (e.g. Treisman and Geffen 1967; Treisman and Riley 1969; Underwood and Moray 1972; Ninio and Kahneman 1974).

The present study examined the effects of varying the rate of delivery of dichotic tone pip stimuli upon selective attention as measured both electrophysiologically (using auditory EP amplitudes) and behaviorally (using signal detectability scores). Inter-stimulus intervals were varied over a range that encompassed those of short duration, as used by Hillyard et al. (1973), intermediate duration like those of Wilkinson and Lee (1972) and Wilkinson and Ashby (1974), and longer ones such as used by Hartley (1970) and Karlin et al. (1970). Finally, this study examined the behavior of the late positive (P_3) component that is elicited when a specific "target" signal is detected within an attended channel (Hillyard et al. 1973). The P_3 was also found to be enhanced with attention but in a fashion that was dissociable from the N_1, substantiating the proposition of Hillyard et al. that these two components are indices of different modes of selective attention.

METHODS

Subjects

Subjects were twelve young adults, seven males and five females. Four were laboratory personnel while the remaining eight were paid student volunteers, only three of whom had had prior experience in similar studies.

Stimulus Presentation

Subjects sat comfortably in a reclining chair inside a sound-attenuated chamber. Through stereo headphones they received two concurrent dichotic sequences of 50 msec tone pips (5 msec rise and fall times). One sequence, presented to the left ear, consisted largely of 1500 Hz tones ("standards") with occasional 1575 Hz tone pips serving as "targets" or "signals". In the right ear, a second sequence was presented consisting of 800 Hz tone pips as standards with occasional 860 Hz tones as "targets". All stimuli were presented at 60 dB SL (above threshold). The sequential order of presentation of tones to right and left ears was randomized (p=0.5 for each ear), as were the time intervals between successive tones and the occurrence of target tones within each channel.

The stimuli were presented to the subjects at three different rates in separate experimental runs. In the "short" inter-stimulus interval conditions, ISIs between tones averaged

350 msec (range 200-500 msec), in the "medium" ISI condition intervals between tones averaged 960 msec (range 400-1520 msec), and in the "long" ISI condition the mean interval was 1920 msec (range 800-3040 msec). The occurrence of a target (signal) within a channel of tones was randomized and unpredictable; during the short ISI condition approximately 10% of the tones in a channel were targets, while this proportion was increased to 20% for both the medium and long ISI conditions so that an adequate number of target EPs could be acquired in a reasonable length of time.

Procedure

Six-minute segments of tape-recorded stimulus sequences were played to each subject, twice at each of the three ISIs. The order of presentation of the ISI conditions was short/medium/long/long/medium/short. Subjects were instructed to attend to only one channel of stimuli during a run and to ignore all stimuli in the other ear. The channel (ear) attended during a run was alternated over the six runs of the experiment; half of the subjects attended to the right ear on the first run and the other half to the left ear. A two-minute rest period intervened between runs.

Subjects were required to respond to the detection of a target (signal) tone in the attended channel by pushing a button within 1.5 seconds. Hits, misses, false alarms and correct rejections were scored for responses to the attended tones. For each experimental run, evoked potentials were averaged separately to the standard (non-signal) and target (signal) tones in each channel.

Recording System

Evoked potentials were recorded from central and parietal scalp locations (Cz and Pz in the international 10-20 system), referenced to the right mastoid, using Grass silver cup electrodes. The vertical electro-oculogram (EOG) was also recorded and averaged to ensure the absence of electro-ocular artifacts. Brain potentials were amplified by Grass 7P5 preamplifiers (bandpass down 3 dB at 0.3 and 500 Hz) and recorded on FM magnetic tape for later analysis. Evoked potentials were averaged using a Nicolet 1072 signal averager in the four channel mode at analyses times of 200 msec and 800 msec (giving a resolution of 1.28 and 0.32 points/msec, respectively). The averaged EPs to the "standard" stimuli in the short, medium and long ISI conditions contained sums of 450, 160 and 80 responses, respectively. For "signals" the EPs during these three conditions were summed over the initial 40, 40 and 20 responses, respectively.

Data Analysis

The N_1 component was quantified as the most negative peak between 80-130 msec post-stimulus onset with respect to a baseline chosen as the mean voltage over the first 20 msec of the averaging epoch (equipment limitations prevented the use of a pre-stimulus baseline). In addition, a peak-to-peak measure was taken with reference to the preceding P_1 component (P_1 being chosen as the most positive peak between 30 and 60 msec after stimulus onset). The P_3 component was quantified as the most positive peak between 300-500 msec, and its amplitude was also measured relative to an initial 20 msec baseline.

The effects of selective listening were evaluated by two measures which compared the amplitudes of N_1 and P_3 components elicited by attended stimuli with the amplitudes produced by the same stimuli when ignored. The first measure, designated the "attention coefficient", was calculated as follows:

$$\text{Attention Coefficient} = \frac{\text{Attend amplitude} - \text{Inattend amplitude}}{1/2\ (\text{Attend amplitude} + \text{Inattend amplitude})}$$

Attention coefficients were calculated separately for each subject, ISI condition, and channel (ear) of stimuli. The expected value of this coefficient is zero if no selective attention effects are present; deviations from zero were assessed using Wilcoxen signed rank tests, treating each coefficient as a weighted "difference score".

The second measure of the selective attention effect was the "per cent enhancement" score, also calculated separately for each subject, ear and condition, defined as:

$$\text{Percent Enhancement} = \frac{\text{Attend amplitude} - \text{Inattend amplitude}}{\text{Inattend amplitude}} \times 100\%$$

RESULTS

Evoked Potentials to Standard (Non-Target) Stimuli

As shown in Figure 1 for a representative subject, the most prominent component in the averaged waveforms was the N_1 wave, peaking about 90 msec after tone onset (range over all subjects was 80-130 msec). The solid lines in Figure 1 depict the evoked vertex potentials under the conditions where the left ear tones were being attended, while the EPs shown by dotted lines were taken when attention was directed to the right ear. When the tone bursts were delivered at the fastest rate ("short ISI's") there was a clear difference in the N_1 amplitudes between attend and ignore conditions for each ear. With increasing ISI, however, one observes a marked reduction in this "attention effect" upon N_1 amplitude. Note too the expected increase in overall N_1 amplitude (and changes in voltage calibration) with the longer ISI ($F(2,22)=82.92<.001$).

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INSERT FIGURE 1 ABOUT HERE

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The mean N_1 amplitude across all twelve subjects and under all conditions are given in the left columns of Table 1 and in Figure 2. During the short ISI condition, the increase in amplitude between attend and inattend conditions averaged 19.8 per cent for the baseline to N_1 measure ($p<.01$ by Wilcoxen, performed on attention coefficients over both ears), and 20.5 per cent for the P_1-N_1 measure ($p<.001$). At medium ISIs, the baseline-peak measure of N_1 showed no significant difference while P_1-N_1 showed a small average effect of 5.6 per cent, ($p<.02$). For the long ISIs, no significant change in N_1 with attention was revealed by either measure.

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INSERT TABLE 1 AND FIGURE 2 ABOUT HERE

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When the standard stimuli were examined on an 800 msec time base (Figure 3 top), no late positive (P_3) component was discernible in the majority of subjects. Accordingly, the P_3 amplitudes plotted in Figure 2 (right column) largely represent the noise level of the baseline-peak positivity in the 300-500 msec zone. Furthermore, the direction of attention was found to have no significant effect on this P_3 measure for the standard stimuli, as indicated by Wilcoxen tests performed on the attention coefficients for P_3 (Table 1).

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INSERT FIGURE 3 ABOUT HERE

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Evoked Potentials to Target Stimuli

In contrast with the standard stimuli, the waveform elicited by the higher pitched targets in the attended ear contained a large positive wave (P_3) peaking at approximately

400 msec (Figure 3 bottom). When the eliciting stimuli were not attended this P_3 was much smaller or absent. The mean amplitudes of the N_1 and P_3 components evoked by targets are given in Table II for the various experimental conditions. The variability of these target-evoked components was much greater than those to the standard stimuli, mainly because fewer responses were included in the averaged waveforms. Despite this variability, significant effects of attention were evident in the target-evoked baseline-N_1 component at the vertex in the short ISI condition (Figure 4). As with the standard stimuli at short ISIs, the N_1s were significantly larger in the ear being attended ($p<.01$ by Wilcoxen test performed on the attention coefficients over both ears).

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INSERT FIGURE 4 AND TABLE II ABOUT HERE

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In the case of P_3 a much smaller amplitude was recorded at Cz than at Pz, such that the P_3 enhancement to attended targets at Cz reached significance only for medium ISIs ($p<.01$). At the Pz electrode locations, however, P_3s to targets in the attended ear were significantly larger than in the opposite ear at all inter-stimulus intervals (Figure 4). In contrast with the N_1 component, it is evident that P_3 amplitudes to targets were not markedly enlarged with increasing ISI ($F(2,22)=1.25$, N.S.); this stability of P_3 occurred despite moderate variations in target probability, target density in time, and target detectability (see below).

Discrimination Performance

From the subjects' responses to target and standard stimuli in the attended channel, the proportions of hits, misses, false alarms and correct rejections were calculated. In the cases of zero false alarm rates, estimated false alarm probabilities were calculated according to the formula used by Moray and O'Brien (1967, Page 766). Averaged over all subjects and both ears, the mean d' for detecting targets in the attended ear was 4.57±.16, for the short ISI condition, 3.54±.11 in the medium ISI condition, and 3.23±.15 in long ISI condition. These differences in d' over the ISI conditions were highly significant as evaluated using a 2-way repeated measures analysis of variance ($F(2,22)=45.14$, $p<.001$). Both d' and percent correct scores are given separately for each ear in Table III.

INSERT TABLE III HERE

DISCUSSION

The previously reported enhancement of the auditory vertex potentials with selective attention to dichotically presented tone pips (Hillyard et al. 1973) was here found to be critically sensitive to the range of inter-stimulus intervals (ISIs) in use. Only at the shortest ISIs (200-500 msec) was there a clear-cut enhancement of the N_1 component (latency 80-130 msec) to stimuli in the attended ear; at intermediate ISI's (400-1520 msec) a marginally significant attention effect was noted, while at the "long" ISIs (800-3040 msec) the direction of binaural attention had no influence upon the N_1 wave. The relative magnitude of this attentional enhancement of N_1 (ca. 20%) with short ISI's was somewhat smaller than in the closely related study by Hillyard et al. (1973, expt. II), probably because the stimulus intensities here were 10 dB louder. In a subsequent report (Schwent et al. 1976b), we found that the auditory vertex potentials to louder stimuli are less labile with shifts of attention than are those to softer stimuli.

The present results strongly suggest that the failure of directed attention to influence the auditory vertex potential, as reported in several laboratories, was in part a consequence of the long ISIs used. In studies by Naatanen (1967, expt. III), Donchin and Cohen (1967), Hartley (1970), and Karlin et al. (1970), the randomized ISI's averaged at least two seconds in duration and thus corresponded to the longer intervals where attentional effects were found to be minimal. In other studies where ISI's were fixed at one second (Smith *et al*. 1970; Wilkinson and Ashby 1974), roughly corresponding to our "medium" ISI range, attentional effects were similiarly absent. The negative results of Smith *et al*. (1970) *vis a vis* the P_1-N_1 measure, however, may well have been due largely to the relatively loud click intensities used (82 dB SPL). Wilkinson and Ashby (1974) did not report their stimulus intensities, nor did they take a measure of N_1 independent of the subsequent P_2 wave; these factors, as well as a fixed ISI duration and a lack of spatial separation of stimulus channels may have contributed to the absence of attention effects on N_1-P_2. Finally, Wilkinson and Lee (1972) employed ISI's that were on the average shorter (673 msec) than those of our "medium" range and did obtain a 10% enhancement of the N_1-P_2 measure to tones in an attended channel, in spite of using rather high tone intensities (61, 72 and 78 dB SPL) and spatially congruous channels; no independent measure of N_1 was reported.

Several possible explanations seem reasonable to explain why short ISI facilitate the channel-selective enhancement of the N_1 wave in these binaural listening tasks. First, placing a large total information load on the subject makes it difficult or impossible for him to process the stimuli in unattended channels when his attentional resources are committed to processing the relevant channel (Norman and Bobrow 1975). Secondly, a high density of stimulation may enable the subject to maintain a more focused state of attention upon the relevant channel, perhaps by continually reinforcing the channel-specific cues or processing steps upon which the selection is based. This idea is supported by the behavioral discrimination data showing that target tones were detected more effectively at the shorter ISIs. A third factor which may influence the magnitude of the attention effect is the marked reduction in N_1 amplitude that occurs at shorter ISIs because of its long recovery period. If selective attention only modulates N_1 over a small amplitude range, any attentional enhancement at longer ISIs may be obscured by its superposition upon a larger and more variable "baseline" N_1.

The present findings demonstrate a clear dissociation between the properties of N_1 and those of the late positive P_3 wave, substantiating the view that "N_1 and P_3 are signs of fundamentally different selective attention processes" (Hillyard et al. 1973). In line with their proposal that N_1 lability reflects a "stimulus set" mode of attention (also termed "filtering" [Broadbent 1971] or "input selection" [Triesman 1969]), the N_1 was enhanced (at short ISIs) to all stimuli in the attended ear (channel), standards and targets alike, in relation to when the other channel was being attended. This would be expected if N_1 indexes a selection mechanism which admits or rejects stimuli on the basis of a preliminary analysis of their simple physical attributes (i.e. their channel of origin).

On the other hand, the P_3 wave was small or absent after all standard stimuli, attended or not, being enlarged only to targets in the attended channel. This suggests that P_3 reflects an attentional process which makes a further selection among stimuli within the channel that has been chosen for analysis by the stimulus set mechanism. Such a process has been designated "response set" or "pigeonholing" (Broadbent 1971) or "target selection" (Triesman 1969) and usually entails an analysis of higher order stimulus attribues through a serial comparison of inputs against stimulus representations in memory. In the present design, for example, it is reasonable to assume that the pitch discrimination between 1500 and 1575 Hz is based largely on a relational comparison of incoming stimuli with the memory traces of recently delivered stimuli (i.e. a response set), rather than an independent identification of each stimulus by its absolute physical attributes. The well-known difference in scalp distribution between N_1 and P_3 (e.g. Picton _et al_. 1974; Simson _et al_. in press) was also verified here, with N_1 being larger over the central scalp and P_3 over the parietal region.

Two further dissociations between N_1 and P_3 were produced by the manipulation of ISI. While the attentional enhancement of N_1 was evident only at the shorter ISIs, the P_3 was substantially enlarged to attended-channel targets at all ISIs, reflecting the generally high detectability of the targets at all ISIs (Table III). Finally, the amplitude of the P_3 to attended targets did not change substantially as a function of ISI, while the attended-channel N_1s were markedly reduced at shorter ISIs. This observation suggests that overall stimulus load has little or no independent influence upon the P_3 amplitude, which is more related to psychological factors such as decision confidence and subjective probability of target occurrence (Squires _et al_. 1975) than is the N_1 amplitude.

SUMMARY

In a selective attention task, twelve subjects received random sequences of 800 and 1500 Hz tone pips in their right and left ears, respectively. They were instructed to attend to one channel (ear) of tones, to ignore the other, and to press a button whenever occasional "targets" tones of a slightly higher pitch were detected in the attended ear. In separate experimental conditions the randomized inter-stimulus intervals (ISI's) were "short" (averaging 350 msec), "medium" (960 msec) and "long" (1920 msec). The N_1 component of the auditory evoked potential (latency 80-130 msec) was found to be enlarged to all stimuli in an attended channel (both targets and non-targets), but only in the short ISI condition. Thus, a high "information load" appears to be a prerequisite for producing channel-selective enhancement of the N_1 wave; this high load condition was also associated with the most accurate target detectability scores (d'). The pattern of attention-related effects on N_1 was dissociated from the pattern displayed by the subsequent P_3 wave (300-450 msec), substantiating the view that the two waves are related to different modes of selective attention.

FOOTNOTES

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REFERENCES

Broadbent, D.E. Decision and Stress. Academic Press, New York, 1971.

Cherry, E.C. Some experiments on the recognition of speech with one and with two ears. J. Acoust. Soc. Amer., 1953, 25: 975-979.

Davis, H. Enhancement of evoked cortical potentials in humans related to a task requiring a decision. Science, 1964, 145:182-183.

Davis, H., Mast, T., Yoshie, N. and Zerlin, S. The slow response of the human cortex to auditory stimuli: recovery process. Electroenceph. clin. Neurophysiol., 1966, 21:105-113.

Debecker, J. and Desmedt, J. Rate of intermodality switching disclosed by sensory evoked potentials averaged during signal detection tasks. J. Physiol., 1966, 185:52.

Donchin, E. and Cohen, L. Averaged evoked potentials and intramodality selective attention. Electroenceph. clin. Neurophysiol., 1967, 22:537-546.

Gross, M.M., Begleiter, H., Tobin, M. and Kissin, B. Auditory evoked response comparison during counting clicks and reading. Electroenceph. clin. Neurophysiol., 1965, 18: 451-454.

Hartley, L.R. The effect of stimulus relevance on the cortical evoked potentials. Quart. J. Exp. Psychol., 1970, 22: 531-546.

Hillyard, S.A., Hink, R.F., Schwent, V.L. and Picton, T.W. Electrical signs of selective attention in the human brain. Science, 1973, 182:177-180.

Hirsh, S. Vertex potentials associated with an auditory discrimination. Psychonom. Sci., 1971, 22:173-175.

Karlin, L. Cognition, preparation and sensory-evoked potentials. Psychological Bulletin, 1970, 73:122-136.

Karlin, L., Martz, M.J., and Mordkoff, A.M. Motor performance and sensory-evoked potentials. Electroenceph. clin. Neurophysiol., 1970, 28:307-313.

Keating, L.W. and Ruhm, H.B. Some observations on the effects of attention to stimuli on the amplitude of the acoustically evoked response. *Audiology*, 1971, *10*:177-184.

Lawson, E.A. Decisions concerning the rejected channel. *Quart. J. Exp. Psychol.*, 1966, *18*:260-265.

Moray, N. Attention in dichotic listening: Affective cues and the influence of instructions. *Quart. J. Exp. Psychol.*, 1959, *11*:56-60.

Moray, N. and O'Brien, T. Signal detection theory applied to selective listening. *J. Acoust. Soc. Amer.*, 1967, *42*: 765-772.

Näätänen, R. Selective attention and evoked potentials. *Annales Academiae Scientiarium Fennicae*, 1967, *B151*:1-226.

Näätänen, R. Evoked potentials and selective attention in humans - a critical review. *Biological Psychology*, 1975, *2*:237-307.

Ninio, A. and Kahneman, D. Reaction time in focused and divided attention. *J. Exp. Psychol.*, 1974, *103*:394-399.

Norman, D.A. and Bobrow, D.G. On data-limited and resource-limited processes. *Cognitive Psychol.*, 1975, *7*:44-64.

Picton, T.W. and Hillyard, S.A. Human auditory evoked potentials. II: Effects of attention. *Electroenceph. clin. Neurophysiol.*, 1974, *36*:191-199.

Picton, T.W., Hillyard, S.A., Galambos, R. and Schiff, M. Human auditory attention: a central or peripheral process? *Science*, 1971, *173*:351-353.

Picton, T.W., Hillyard, S.A., Krausz, H.I. and Galambos, R. Human auditory evoked potentials. I: Evaluation of components. *Electroenceph. clin. Neurophysiol.*, 1974, *36*: 179-190.

Satterfield, J.H. Evoked cortical response enhancement and attention in man. A study of responses to auditory and shock stimuli. *Electroenceph. clin. Neurophysiol.*, 1965, *19*:470-475.

Schwent, V.L. and Hillyard, S.A. Evoked potential correlates of selective attention with multi-channel auditory inputs. *Electroenceph. clin. Neurophysiol.*, 1975, *38*:131-138.

Schwent, V.L., Hillyard, S.A. and Galambos, R. Selective attention and the auditory vertex potential II: Effects of signal intensity and masking noise. Submitted to *Electroenceph. clin. Neurophysiol.*, 1976b.

Shiffrin, R.M. and Grantham, D.W. Can attention be allocated to sensory modalities? *Perception and Psychophys.*, 1974, 15:460-474.

Simpson, R., Vaughan, H.G., Jr. and Ritter, W. The scalp topography of potentials associated with missing visual or auditory stimuli. *Electroenceph. clin. Neurophysiol.*, (In press).

Smith, D.B.D., Donchin, E., Cohen, L., and Starr, A. Auditory averaged evoked potentials in man during selective binaural listening. *Electroenceph. clin. Neurophysiol.*, 1970, 28:146-152.

Squires, K.C., Squires, N.K. and Hillyard, S.A. Vertex evoked potentials in a rating-scale detection task: relation to signal probability. *Behavioral Biol.*, 1975, 13: 21-34.

Treisman, A.M. Strategies and models of selective attention. *Psychol. Rev.*, 1969, 76:282-299.

Treisman, A.M. and Geffen, G. Selective attention: Perception or response? *Quart. J. Exp. Psychol.*, 1967, 19:364-367.

Treisman, A.M. and Riley, J.G.A. Is selective attention selective perception or selective response? A further test. *J. Exp. Psychol.*, 1969, 79:27-34.

Underwood, G. and Moray, N. Shadowing and monitoring for selective attention. *Quart. J. Exp. Psychol.*, 1972, 23: 284-296.

Wilkinson, R.T. and Ashby, S.M. Selective attention, contingent negative variation and the evoked potential. *Biological Psychology*, 1974, 1:167-179.

Wilkinson, R.T. and Lee, M.V. Auditory evoked potentials and selective attention. *Electroenceph. clin. Neurophysiol.*, 1972, 33:411-418.

Wilkinson, R.T. and Morlock, H.C. Auditory evoked response and reaction time. *Electroenceph. clin. Neurophysiol.*, 1967, 23:50-56.

TABLE I

Mean amplitudes (μV) of N_1 and P_3 components to standard stimuli and mean derived attention scores under the different experimental conditions (±S.E.)

	Evoking Stimulus	Attended Stimulus	Baseline-N_1 (Cz)	P_1-N_1(Cz)	Baseline-P_3 (Pz)
		Left	3.37±0.54	4.83±0.66	0.27±0.65
	Left	Right	2.46±0.63	3.62±0.67	0.98±0.21
hort SI		Left	2.62±0.43	4.03±0.62	1.52±0.33
	Right	Right	3.17±0.57	4.50±0.68	1.08±0.39
	Percent Enhancement		19.8±10.6%	20.5±4.9%	
	Attention Coefficient		(.312±.114)**	(.222±.060)***	(-1.134±.528)
		Left	7.53±1.00	9.06±1.07	1.25±0.84
	Left	Right	7.28±1.03	8.51±0.96	0.12±0.89
edium SI	Right	Left	6.98±0.54	8.30±0.83	0.82±0.54
		Right	7.71±0.78	8.73±0.79	0.12±0.78
	Percent Enhancement		1.4±6.7%	5.6±2.6%	
	Attention Coefficient		(0.062±.070)	(0.062±.026)*	(.058±.790)
		Left	8.68±0.90	9.52±1.01	0.97±1.42
	Left	Right	9.02±1.26	10.02±1.35	0.07±1.26
ong SI		Left	9.03±0.97	10.72±1.13	0.25±1.24
	Right	Right	10.19±0.92	12.33±1.10	0.55±1.47
	Percent Enhancement		4.5±5.3%	3.8±5.6%	
	Attention Coefficient		(.074±.052)	(.072±.056)	(.058±.538)

***	$p<.001$
**	$p<.01$
*	$p<.02$

TABLE III

Mean d' and per cent correct scores (±S.E.) averaged over all subjects under the different experimental conditions.

		d'	Per Cent Correct
Short ISI	Attend Left	4.56±.16	95.2±1.2
	Attend Right	4.57±.19	94.3±1.6
	Combined	4.57±.16	94.7±1.0
Medium ISI	Attend Left	3.57±.14	89.9±1.4
	Attend Right	3.51±.14	86.8±1.9
	Combined	3.54±.11	88.4±1.2
Long ISI	Attend Left	3.44±.17	90.7±2.3
	Attend Right	3.01±.16	83.8±2.3
	Combined	3.23±.15	87.3±1.7

TABLE II

Mean amplitudes (μV) of N_1 and P_3 components to target (signal) stimuli and significant attention coefficients under the different experimental conditions (±S.E.)

			Cz			Pz		
	Evoking Stimulus	Attended Stimulus	Baseline-N_1	P_1-N_1	Baseline-P_3	Baseline-N_1	P_1-N_1	Baseline-P_3
Short ISI	Left	Left	5.81±0.85	6.92±0.93	4.43±1.24	4.18±1.17	5.71±1.00	6.02±1.26
		Right	2.53±0.87	4.63±0.75	3.29±0.68	2.54±1.00	4.51±0.95	4.06±0.89
	Right	Left	3.28±0.76	4.87±0.87	2.43±0.66	3.54±0.93	5.23±1.44	2.52±0.41
		Right	5.08±0.83	7.02±0.86	4.10±1.80	4.25±1.23	6.05±0.98	6.55±1.30
	Attention Coefficient		(.702±.202)**					(.554±.204)**
Medium ISI	Left	Left	5.72±1.52	9.10±1.40	3.83±1.40	6.01±2.18	8.08±2.21	3.83±1.22
		Right	8.07±1.29	9.80±1.15	1.20±0.83	7.59±2.09	9.08±2.08	0.80±0.83
	Right	Left	8.19±0.96	10.01±1.17	0.30±0.89	6.85±1.59	8.43±1.65	0.38±0.94
		Right	8.90±1.08	10.93±1.22	3.23±1.34	7.15±1.72	9.20±1.93	5.38±1.23
	Attention Coefficient				(1.274±.552)**			(1.402±.346)***
Long ISI	Left	Left	9.67±1.56	11.38±1.18	4.02±1.32	7.71±2.51	9.60±2.30	7.64±1.44
		Right	8.25±1.35	10.14±1.54	2.24±1.21	6.76±2.18	9.09±2.63	2.27±1.00
	Right	Left	10.07±1.85	11.74±1.78	2.28±1.35	8.17±2.37	9.15±1.98	2.45±1.20
		Right	9.75±1.28	11.15±1.46	1.37±1.16	8.05±1.86	10.68±2.05	4.11±1.49
	Attention Coefficient							(1.038±.360)**

*** $p<.001$
** $p<.01$

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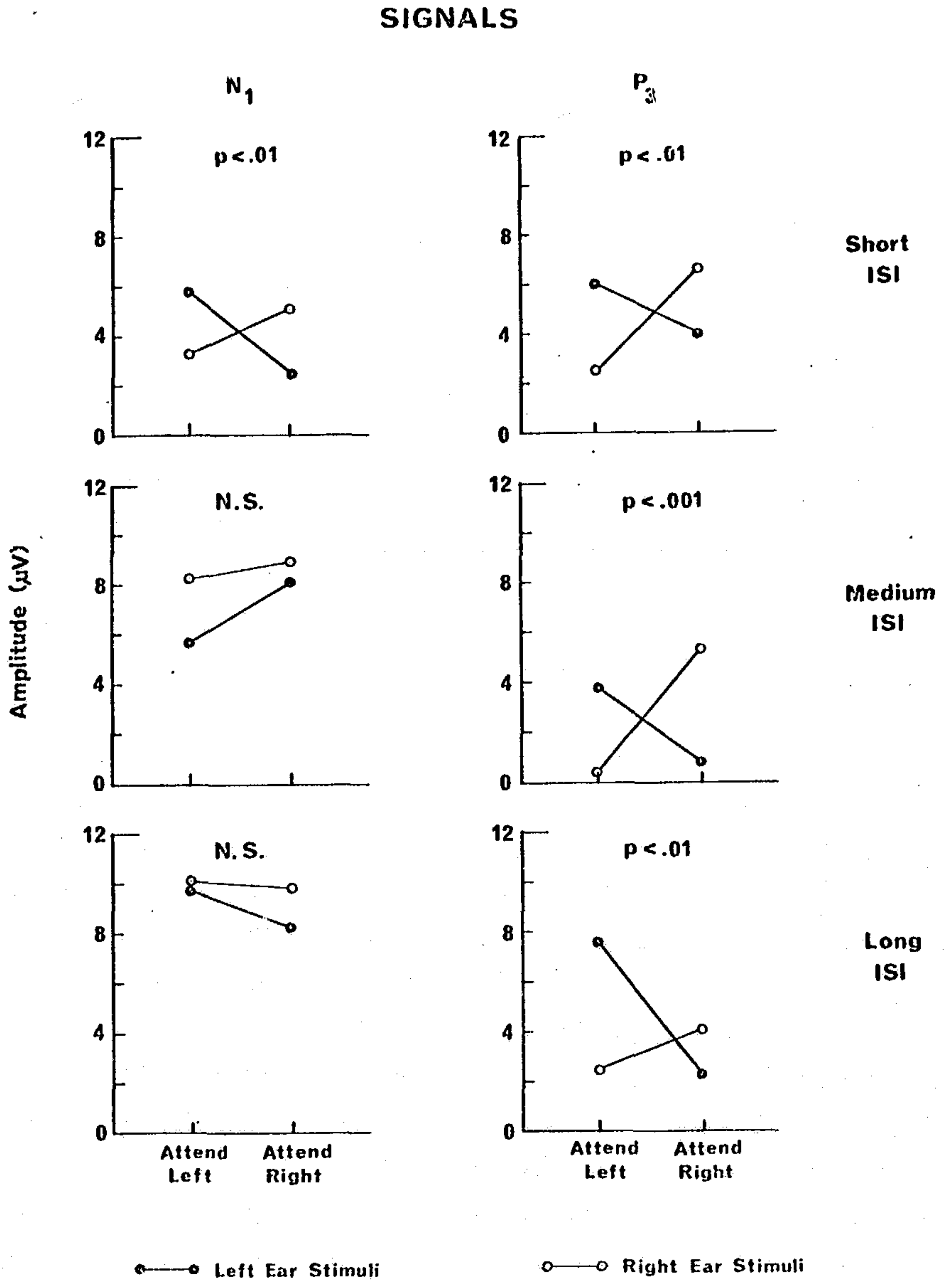
FIGURE LEGENDS

Figure 1 Averaged EP waveforms to standard stimuli from one naive subject (A.H.). Attending to the left ear tones (solid lines)enhanced the N_1 amplitude to those tones in the short ISI condition only. Likewise, attending to right ear tones of 800 Hz (dotted lines) enhanced the N_1s evoked by those stimuli.

Figure 2 Mean amplitudes of baseline-N_1 and baseline-P_3 components (at Cz and Pz, respectively) elicited by standard stimuli in right and left ears under attend-right and attend-left conditions, for each of the three ISIs. The indicated significance levels were obtained from Wilcoxen tests performed on the attention coefficients derived from these data and combined for both ears.

Figure 3 Evoked potential waveforms recorded from Pz in one subject (E.S.) to target (signal) and non-target (standard) tones during the "short" ISI condition. Responses to standard tones (N=256) show little or no significant change in the late components with the direction of attention (solid lines = attend left; dotted lines = attend right). Responses to the signal tones, however, (N=32) show the addition of a large P_3 wave at 350-400 msec to stimuli in the attended ear.

Figure 4 Mean amplitudes of baseline-N_1 and baseline-P_3 components (at Cz and Pz, respectively) elicited by target stimuli in right and left ears under attend-right and attend-left conditions for each of the three ISIs.



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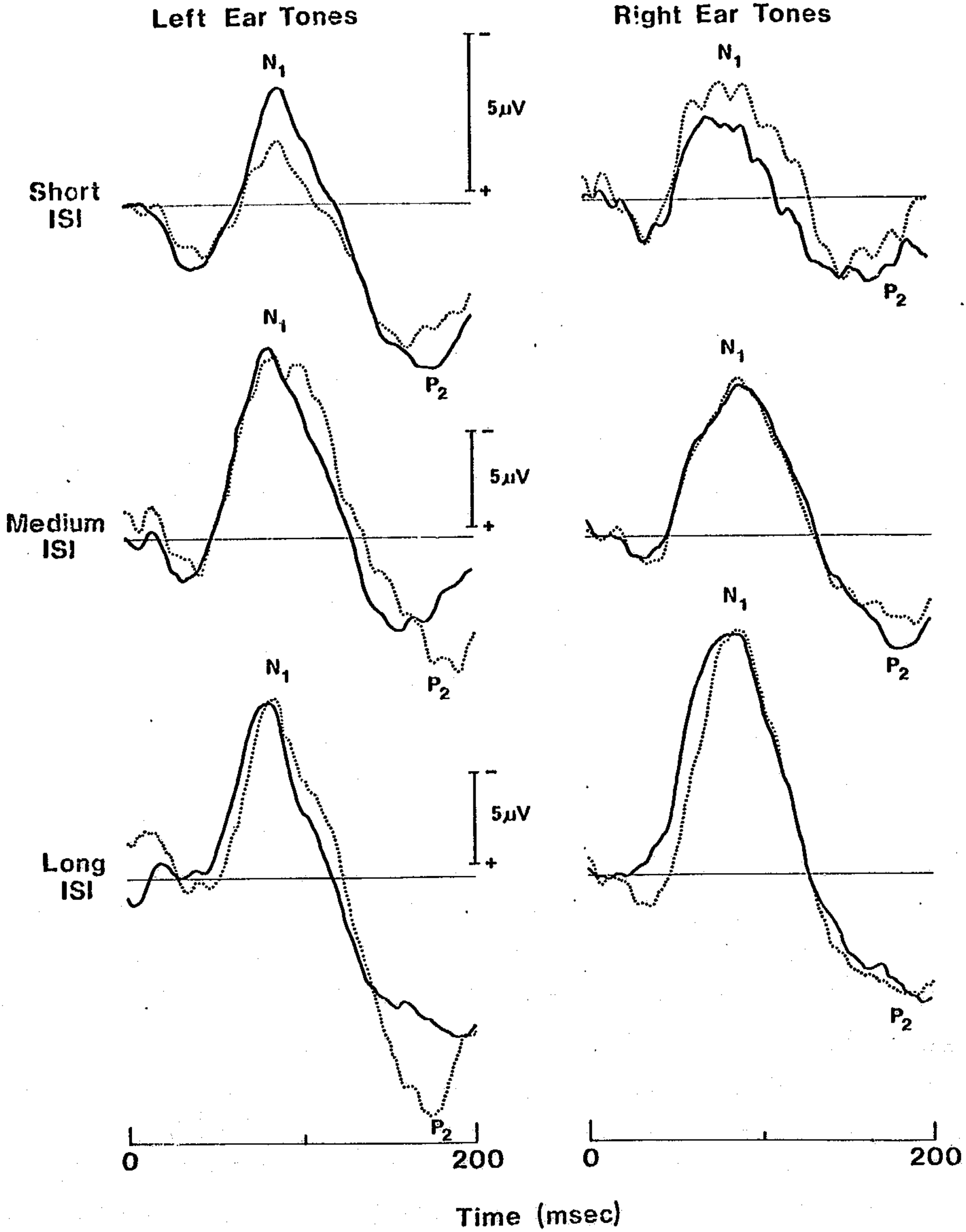
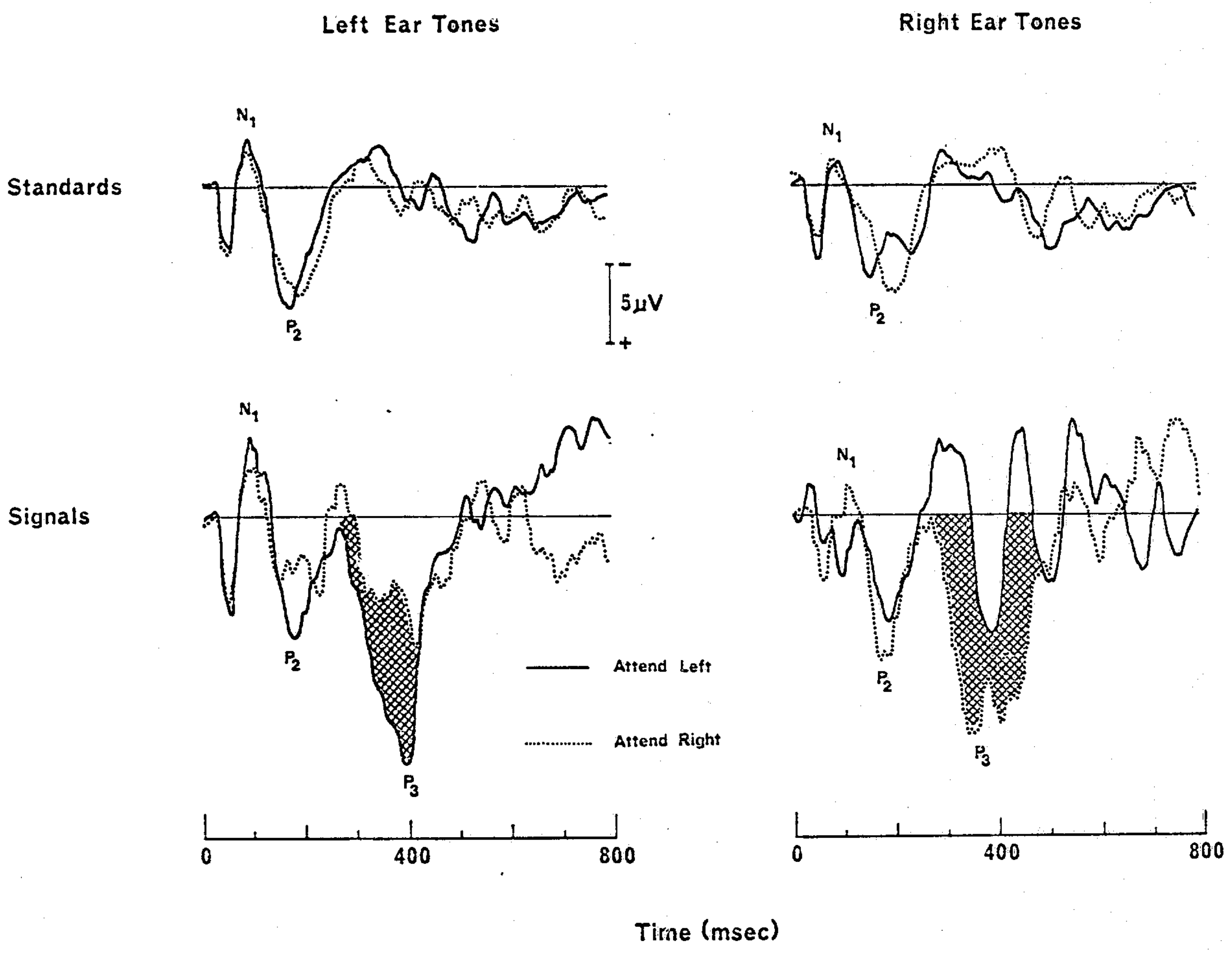
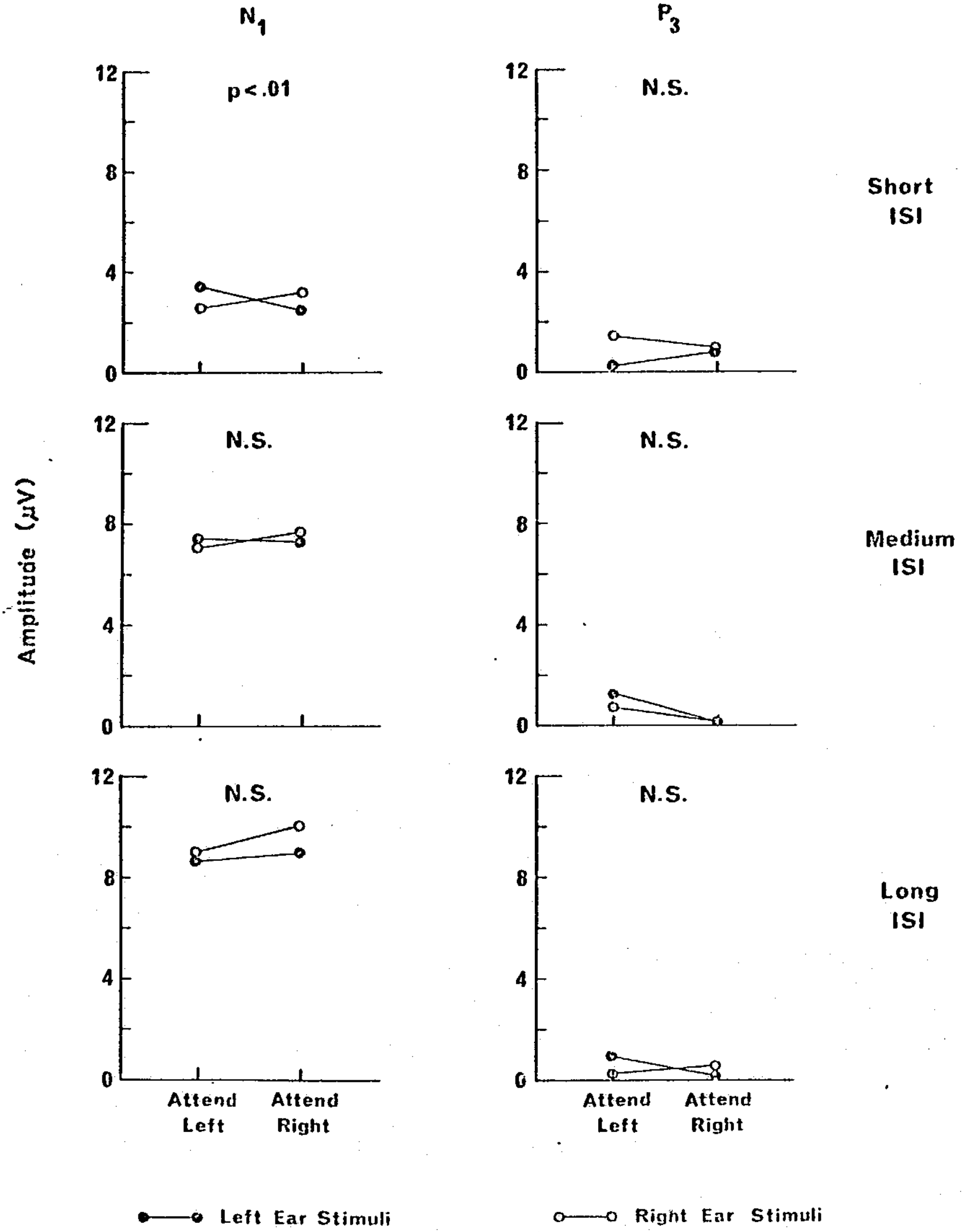

Left Ear Tones
Right Ear Tones
Short ISI
Medium ISI
Long ISI
N1
P2
5µV
−
+
0
200
Time (msec)


Left Ear Tones
Right Ear Tones
Standards
Signals
N1
P2
P3
5µV
−
+
Attend Left
Attend Right
0
400
800
Time (msec)

STANDARDS


N1
P3
12
8
4
0
p<.01
N.S.
N.S.
N.S.
N.S.
N.S.
Amplitude (µV)
Short ISI
Medium ISI
Long ISI
Attend Left
Attend Right
Attend Left
Attend Right
●——● Left Ear Stimuli
○——○ Right Ear Stimuli