

Evidence for Effects of Selective Attention in the Mid-Latency Range of the Human Auditory Event-Related Potential

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Selectively attending to a particular stimulus in the environment results in improved processing of that input relative to other, non-attended inputs. A controversy exists as to whether or not this stimulus selection may involve the early 'gating' or filtering of irrelevant sensory input. Although the older studies with animals that purported to have demonstrated peripheral sensory gating have been criticized on methodological grounds (e.g., by Worden 1966), more recently a number of better controlled animal studies have presented evidence that early auditory processing in the eighth nerve and brain-stem (Oatman 1971, 1976; Oatman and Anderson 1977) and primary cortex (Benson and Heinz 1978) can be modulated as a function of attention.

The physiological and psychological mechanisms of selective attention can be investigated in humans by means of event-related potentials (ERPs) recorded from the scalp. The earliest components of the auditory ERP, the brain-stem evoked responses (BERs, latency range 2–8 msec) and the mid-latency responses (MLRs, latency range 10–40 msec) have generally not demonstrated any reproducible changes as a function of attentional manipulations (Picton et al. 1971; Picton and Hillyard 1974; Picton et al. 1978; Woods and Hillyard 1978). There have been some reports, however, of short-latency attention effects on the auditory ERP. Lukas (1980, 1981) reported finding changes in tone-evoked BERs when subjects switched from auditory to visual attention (although Picton et al. (1981) failed to replicate these results using a similar paradigm). Changes in click-evoked BERs have also been reported as a function of attention/distraction (Brix 1984) and during speech production (Papanicolaou et al. 1986). An attention effect in the mid-latency range was reported by McCallum et al. (1983) in a study investigating selective attention to sounds at different spatial locations; in their study a 'P26' component, identified through principal components analysis, was reduced for attended sounds.

The earliest attention effect that has been consistently observed in the human

auditory ERP has been called the 'N1 effect' or the 'Nd' wave, which is a negative difference between ERPs elicited by attended stimuli relative to ERPs elicited by ignored stimuli (reviewed in Hillyard and Kutas 1983). This wave onsets as early as 60 msec, typically enhances the measured amplitude of the evoked N1 component, and seems to behave like an index of an early 'stimulus set' selection of input channel (Hillyard et al. 1973; Hansen and Hillyard 1983). However, it has been argued that 60 msec could be sufficient time for perceptual analysis of the channel-defining cue to have occurred and, therefore, that the Nd does not necessarily reflect a tonically maintained prestimulus set (Näätänen and Michie 1979).

The purpose of the two dichotic listening experiments reported here was to take a further look at the effects of highly focussed selective attention on the human auditory ERP. The experiment conditions were designed to optimize early selective attention effects: (1) the channel separation was made as wide as possible, with two channels of tones being distinguished by both ear of entry and by frequency; (2) the stimulus rate, and therefore processing load, was made very high; and (3) the task of target detection was made very difficult to force the subjects to attend closely to all the sounds within the designated channel (reviewed in Hillyard and Picton 1979; see also Hansen and Hillyard 1980, 1984). In addition, large numbers of stimuli were presented so as to achieve averaged responses with high signal/noise ratios.

METHODS

Experiment 1

Ten female subjects (ages 19–28, 8 right-handed) listened through stereo headphones to tone sequences consisting of 5000 Hz tone pips (duration 1.0 msec) to the left ear and 3400 Hz tone pips (duration 1.5 msec) to the right ear. These tones were presented dichotically in random order with ISIs ranging between 120 and 320 msec (rectangular distribution). The task was to listen selectively to the tones in one ear at a time and to press a button upon detecting occasional (10% per ear), difficult-to-detect 'target' tones of lesser intensity than the 60 dB SL 'standard' tones. Following a preliminary session in which subjects were trained to a criterion performance level, 12 runs each of Attend Left and Attend Right conditions were presented in counterbalanced order, giving a total of 2400 'standards' in each averaged response.

Brain electrical activity was recorded using Ag/AgCl electrodes. Two parallel recording systems were employed. One system consisted of two high-resolution 'fast' channels (digitization rate 25,000 Hz/channel) that performed on-line averaging of evoked responses from Cz referred to each mastoid using a bandpass (30–3000 Hz) and epoch length (20 msec) appropriate to BERs. Slower waves (MLRs and late waves) were recorded in a parallel system that performed continuous digitization onto tape (500 Hz/channel, bandpass 0.01–100 Hz) of the EEG from 11 scalp sites of the international 10-20 system (Fpz, Fz, C3, Cz, C4, Pz, T3, T4, T5, T6, and right mastoid), all using the left mastoid (Lm) as reference. ERPs were subsequently extracted from the digitized EEG data by averaging off-line in 512 msec epochs and were then re-

referenced by appropriate subtractions to the averaged mastoids. Electro-ocular activity (EOG) was also recorded in this system for use in artifact rejection during the off-line averaging process.

Experiment 2

To test the generality of the effects found in the first experiment, a replication was carried out with different stimulus parameters. The tone pips were longer in duration (13 msec), slower in rise-time (5 msec), slightly fainter (by 5 dB SL), and lower in frequency (1500 Hz in the left ear, 2600 Hz in the right). Sixteen new subjects (ages 18–26, all female, 13 right-handed) and new randomized stimulus sequences were used, but target probability and ISI range were identical to experiment 1. The number of runs in each condition was increased by 33%, raising the total number of stimuli per subject included in each of the standard-tone averages to 3200. No attempts were made to look at BERs, as the two 'fast' channels were set at a bandpass (3–300 Hz) and epoch length (80 msec) to optimize recording of MLR activity. The slower channels (bandpass 0.1–100 Hz) included a balanced sterno-vertebral, non-cephalic placement referenced to left mastoid to enable later re-referencing of scalp channels against the non-cephalic lead.

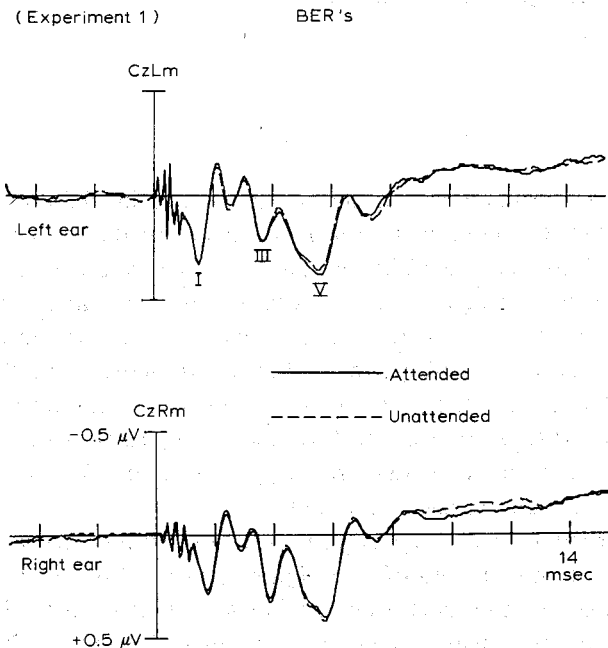


Fig. 1. Grand-averages ($N = 10$) BERs recorded in experiment 1. Vertex to ipsilateral mastoid recordings with bandpass 30–3000 Hz. BERs to left ear standard tones are at top, BERs to right ear standard tones at bottom. In each plot, the solid line is the response when the tones were attended and the dashed line is the response to the same tones when they were unattended. There was no effect of attention on these components as can be seen by the close superposition of the attended and unattended waveforms. The high-frequency signal in the first millisecond of the records is stimulus artifact picked up by magnetic induction from the headphones.

RESULTS

Although both short- and long-latency ERP components were recorded in these studies, the emphasis of this report will be on attention effects at early latencies. Statistical comparisons (repeated measures ANOVA) were made between the ERPs elicited by standard stimuli when attended and the ERPs elicited by those same stimuli when unattended. Thus, any difference between attended and unattended ERPs would be attributable solely to the internal shifting of attention to the designated ear. All figures shown here are grand averages to the standard tones.

Effect on BERs (experiment 1 only)

As can be seen in Fig. 1, switching attention from one ear to the other had no influence on the BERs. Statistical comparisons for baseline-peak and peak-to-peak measures of the principal BER components (waves I–V) showed no significant effects of attention.

Effects on mid-latency components

Experiment 1. The auditory ERPs on a longer time-base showed a significant attention effect in the MLR range. Peak-to-peak amplitudes of Na to Pa were significantly larger (20–35%) for attended ear stimuli at central/frontal scalp sites (see Table I). This measure was performed by a computer algorithm that determined the amplitude difference between the largest positive peak and the preceding largest negative peak in the Na–Pa latency range (14–36 msec). Fig. 2 shows the attention effect at the Fz site by juxtaposing the original attended and unattended waveforms for each ear with

TABLE I
EXPERIMENT 1

Na–Pa peak-to-peak amplitudes as a function of attention, collapsed over left and right ears (reference = averaged mastoids).

Site*	Amplitudes ($\mu\text{V} \pm \text{S.E.}$)		$F(1, 9)$	P value
	Attended	Unattended		
Fpz	0.77 ± 0.08	0.62 ± 0.05	6.36	<0.03
Fz	0.77 ± 0.09	0.60 ± 0.06	6.90	<0.03
C3	0.63 ± 0.08	0.46 ± 0.06	10.12	<0.01
Cz	0.67 ± 0.10	0.50 ± 0.08	7.84	<0.02
C4	0.60 ± 0.09	0.48 ± 0.07	11.33	<0.01
Pz	0.35 ± 0.06	0.28 ± 0.05	4.45	n.s.
T3	0.45 ± 0.04	0.37 ± 0.03	10.25	<0.01
T4	0.43 ± 0.05	0.38 ± 0.05	4.68	n.s.

* Only those sites have been included for which Na–Pa components were large enough to be validly measured.

their associated difference waves (attended ERP – unattended ERP). The mid-latency attention effect appears as a greater positivity to attended ear stimuli over the latency range 20–50 msec and, therefore, has been labeled the 'P20–50' in Fig. 2.

Experiment 2. The P20–50 attention effect was replicated, although its amplitude was somewhat smaller (see Table II). For the 'fast' recordings (see Fig. 3), the Na–Pa peak-to-peak amplitudes (collapsed over left and right ears) averaged 13% larger for attended stimuli for Cz–Lm, and 10% larger for Cz–Rm. In the longer time base recordings (no waveforms shown), Na–Pa peak-to-peak amplitudes were significantly larger (10–18%) for attended stimuli at Fz, C3, Cz, and C4 with left mastoid reference (Table II). On re-referencing to the non-cephalic reference, the Na–Pa amplitude tended to be larger for attended stimuli at these 4 sites, but this effect was significant only for C3 ($F(1, 15) = 7.19, P < 0.02$). This difference may be explained by the tendency for the non-cephalic leads to be consistently noisier.

Effects on long-latency components

The principal effects of attention on the later waves were very similar in experiments 1 and 2. At Fz and central scalp sites the Nd wave appeared in two distinct phases, the

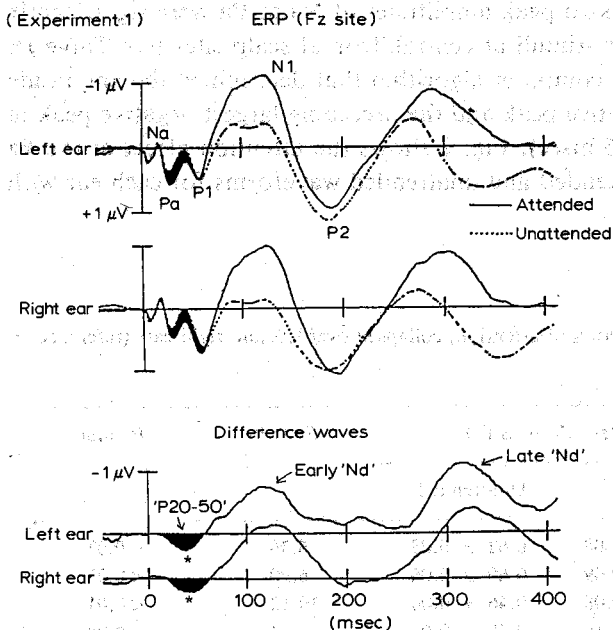


Fig. 2. Grand-average ($N = 10$) ERPs and difference waves from experiment 1. Both mid-latency and long-latency activity can be seen. Data are from Fz site referred to averaged (not linked) mastoids, with bandpass of 0.01–100 Hz. The top two plots display the ERPs to the standard tones to the left ear or right ear, as labeled. Solid lines represent the ERPs when the tones were attended and dashed lines when unattended. The P20–50 attention effect (darkened area) appears as an enhanced positivity between 20 and 50 msec in the attended ERP. This can also be seen in the difference waves (attended ERP – unattended ERP), shown at bottom. These plots also show the complete separation of the Nd into two distinct phases.

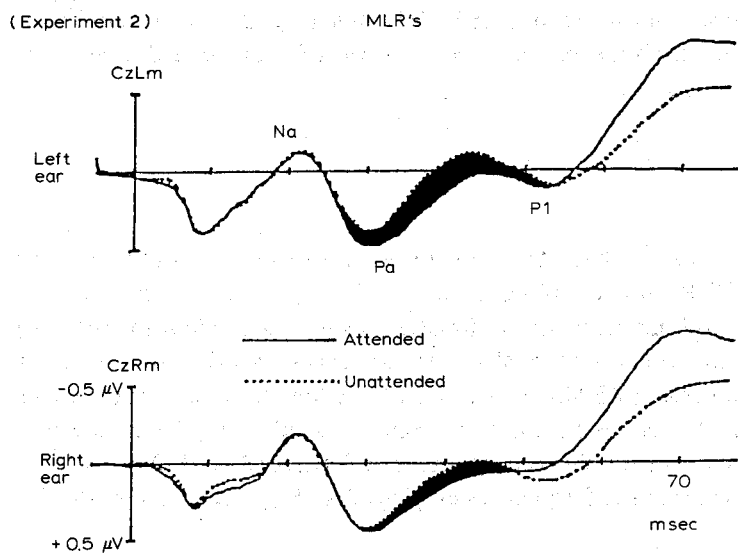


Fig. 3. Grand-average ($N = 16$) MLRs from experiment 2. Recordings were from Cz referred to ipsilateral mastoid with bandpass 3 – 300 Hz. Solid lines depict MLRs elicited to standard tones when they were attended and dashed lines when unattended. The P20 – 50 attention effect (darkened area) appears as enhanced positivity between 25 and 50 msec in the attended ERPs.

TABLE II

EXPERIMENT 2

Na – Pa peak-to-peak amplitudes as a function of attention, collapsed over left and right ears.

Site*	Amplitudes ($\mu\text{V} \pm \text{S.E.}$)		$F(1, 15)$	P value
	Attended	Unattended		
<i>Fast channels</i>				
Cz-Lm	0.74 ± 0.06	0.65 ± 0.05	6.93	<0.02
Cz-Rm	0.80 ± 0.05	0.72 ± 0.05	4.59	<0.05
<i>Slower channels (reference = left mastoid)</i>				
Fpz	0.63 ± 0.05	0.63 ± 0.05	0.03	n.s.
Fz	0.74 ± 0.06	0.68 ± 0.06	6.93	<0.02
C3	0.64 ± 0.06	0.54 ± 0.05	23.81	<0.001
Cz	0.67 ± 0.05	0.58 ± 0.05	8.56	<0.01
C4	0.59 ± 0.05	0.53 ± 0.04	5.50	<0.03

* Only those sites have been included for which Na – Pa components were large enough to be validly measured.

first spanning 50–160 msec and the second 250–500 msec (Fig. 2). At the more frontal Fpz site, however, the attention effect took the form of a prolonged continuous negativity (not shown).

DISCUSSION

Even though the conditions of these experiments were intended to optimize early stimulus selection, the BERs still remained invariant. Thus, these data provided no evidence for gating or modulation at the brain-stem level as a mechanism for early selective attention. This invariance of the BERs also argues against differential activation of the middle ear muscles (MEMs) as a cause of the longer latency attention effects. Such an effect of MEMs would not have been expected in any case, however, because: (1) MEM activity is generally non-voluntary and bilateral, and (2) MEM contraction has limited influence at the frequencies employed in the present studies (Møller 1974).

The present experimental conditions did result in an attention effect in the midlatency range. The P20–50 difference wave peaked around or just after the Pa wave, a component that may reflect early activity in or near primary auditory cortex (Celesia 1976; Kraus et al. 1982; Kileny et al. 1987). Whether the P20–50 derives from an enhancement of Pa generators, or whether it is a separate, broader wave that originates from a different set of sources, is not clear. In any case, because of the very early onset of this effect (20 msec), these data strongly support the 'early selection' hypothesis (reviewed in Johnston and Dark 1982) that stimulus processing can be selectively tuned or biased before full analysis has occurred. Presumably this is achieved by means of a tonically maintained pre-stimulus set.

It is unlikely that the P20–50 effect is a result of myogenic contamination, such as might arise from the auditory evoked post-auricular muscle response (PAR). This is because: (1) subjects were screened so as to reject those with appreciable background muscle activity and/or any discernible evoked muscle responses; (2) the topographic distribution (central-midline maximum amplitude) and waveform shape (broad, monophasic) of the P20–50 effect were inconsistent with what would be expected from evoked PAR activity; and (3) a recent study in our laboratory (Hackley et al. in press) using a similar paradigm, but under conditions optimized to elicit and record evoked PAR activity, found no effect of attention to a stimulus on its elicited PAR. Thus, the attention effect would appear to be neural in origin.

Finally, under the present conditions that enabled the P20–50 effect to appear, the Nd (first phase) also began quite early, immediately following the P20–50. However, this early phase of the Nd still did not begin any earlier than the onset of the evoked N1 component to unattended tones (that is, the negative-going limb that followed the unattended P1 peak). In fact, the early Nd phase seemed to overlap in time quite closely with the unattended N1 (Fig. 2). This suggests that a limit may exist on how early the Nd can begin, a limit that could be imposed if the early part of the Nd is either: (1) made up predominantly from enhanced activity of one or more of the N1 generators

themselves, or (2) dependent on completion of pre-N1 activity. Such consideration could explain why very early auditory selection may be reflected in the P20–50 wave rather than in a progressively earlier Nd. The extent to which the P20–50 is separable from the early Nd as opposed to being an integral part of the same neural subsystem remains to be determined.

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