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<p>This annual report describes the five channel neuromagnetometer operating at NYU, and the principles underlying its use. It further describes recent advances in methodology, including the results of a theoretical study showing that measurement of the field at at least five different positions is needed to fully characterize a single dipole source. The number of recording positions increases markedly with noise. Therefore, a shielded environment would minimize the number of recording sessions required for a neuromagnetic study. The report also provides a history of the work in relevant areas, and goes on to describe a completed study of selective auditory attention. It was found that magnetic counterparts of N100 and P200 of the event related potential show a strong effect of attention in a dichotic listening task. The magnetic components (N100m and P200m) can be accounted for by sources located in the auditory cortex, and do not change in position or depth with attention. The effect of attention is to change the tangential current dipole moment. Analysis of variance (ANOVA) using the field measurements near</p>			
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> field extrema show that the only effect of significance is that of the instruction to attend or not to attend to the stimulus. This result is reflected in the change in source intensity (dipole moment). The results are consistent with an early filter theory of attention, and seem to be inconsistent with the "analysis by synthesis" approach. Moreover, the results suggest that the filtering operations associated with selective attention occur in the primary sensory projection areas, although roles for other areas cannot be completely ruled out. Even so, it appears that there are no other sources that contribute to the effect of attention on N100m or on P200m, despite the conjectures of other investigators that, e.g., frontal sources may contribute to the electrical counterparts to them. It is also reported that a similar experiment reveals specific effects of selective visual attention on areas in the visual cortex. However, this work is still underway, since it also appears that slight shifts in eye fixation may contaminate results in a vision experiment.



labile, e.g., more readily affected by levels of arousal or by shifts in the deployment of attention. To study these "event-related fields" it is necessary to avoid the assumption of stationarity. The only simple way in which to do this is to measure the field at several places outside the head at the same time. Replications of measurements at or near some of these places while measuring the field at more distant places enable one to determine if the source of the observed field is indeed the same from one trial to the next. Moreover, as we will see below, the sources can remain stable only if there is excellent experimental control over the subject's mental activity.

There is still another reason justifying multiple-channel instruments. This is the reason of experimental economy. The creation of several contour maps showing the response field distribution over the head corresponding to effects of different stimulus parameters requires many long hours of experimentation. If the field could be measured at only one place at a time, the dewar and perhaps the head of the subject would have to be repositioned from one trial to the next. Moreover, it is vital to know the spatial position at which the field is measured with a high degree of precision. Otherwise it would be impossible to make accurate contour maps for the purpose of identifying the position and orientation of the source within the head. We will not discuss the latter problem here except to say that new methods have already been developed for the automatic recording of the head's position and orientation relative to the detection coils within the dewar, and these new methods are currently being tested. However, we shall discuss the development of multiple channel instruments and their use at NYU.

In the course of this project we collaborated with Biomagnetic Technologies, Inc. (BTi) in developing and constructing a 5-channel system (11). The individual coils of the five second-order gradiometers in this system are 1.5 cm in diameter with the end sets separated from the middle set by 4 cm (the "baseline" of the gradiometer). The bottom coils ("pick-up coils") of the gradiometers have a center-to-center separation of 2 cm from each other, with the axes of the outer four coils tipped by 10 deg from the dewar axis so that each coil points to a common position 9 cm below the bottom of the dewar. While we relied upon the mechanical positioning of superconducting tabs to obtain field balance in our single-sensor system, as did Romani et al. (12) for a 4-sensor system, we adopted a totally new procedure in this system. Instead we incorporated three rf-SQUID magnetometers for monitoring the field in three orthogonal directions just above the detection coils and a simple first-order gradiometer for monitoring the field gradient along the axis of the dewar. The outputs of these ancillary devices are given empirically determined weights, and then subtracted from the outputs of each of the five signal channels. This "electronic" field balancing yields results comparable to those obtained with the mechanical field balancing for the single-channel instrument. The noise level above about 4 Hz in each channel, after subtracting the weighted outputs of the references, is about 20 femtotesla (fT) per root Hz of bandwidth. However, at lower frequencies the noise amplitude increases at a rate that is slightly faster than the inverse of the frequency. This effect of ambient magnetic noise is pervasive, and it seriously restricts our ability to measure very slowly changing fields. Excess noise at power line frequencies is largely removed by comb filters.

Our experience with this system convinced us that it is indeed possible to place a large number of channels in close proximity to each other within a single dewar, i.e., the "cross talk" between channels was less than 1 %. Since we were also thinking in terms of clinical applications, it became increasingly obvious that it will ultimately be necessary to monitor the field over the entire scalp at once. Although many technical problems remain, we consider it feasible to construct a system composed of about 100 channels within a single dewar.

It is becoming clear, however, that even with electronic balancing for field and its second-order gradient - methods in use in more advanced 7-channel systems, such as those installed at Bellevue and at UCLA - the low-frequency noise level may not be acceptable for all state-of-the-art neuromagnetic measurements. For instance, there is increasing interest in slowly varying phenomena related to higher levels of brain function, such as cognition. It appears that these can be studied most effectively in a clinical or laboratory setting through use of a magnetically shielded room to better reduce low frequency magnetic noise. Several types of rooms have been described in the literature for use in noisy environments (13,14), although simpler ones may suffice in clinics and laboratories in suburban or rural areas.



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## ANALYSIS

### 1. Implications of Multiple Measurements

While work is progressing along several different lines toward the goal of resolving and locating sources of neuromagnetic fields, in this section we shall focus on the implications of using multiple sensors for source localization. Our motivation for employing 14 sensors is perhaps best explained by considering the precision with which field measurements can locate the simplest neural source: a confined region of activity that can be modeled by an equivalent current dipole. Such a dipole is characterized by 5 parameters: the strength  $Q$  of its moment tangential to the scalp (the normal component is magnetically silent); transverse position  $x$  and  $y$  in the tangent plane; depth  $D$  beneath the scalp; and orientation  $\Psi$  in the tangent plane. Therefore, in principle, a 5-sensor probe is sufficient to determine the parameters with simultaneous measurements at a single, appropriate position. Computations for the case where the probe is centered on one of the two field extrema show that while this is indeed true, the presence of a typical level of magnetic noise introduces considerable uncertainty in the values of these parameters (15). Table I illustrates this in comparison with the uncertainties for systems with a single 7-sensor probe and a pair of 7-sensor probes similar to those installed at Bellevue, since these are the most advanced available systems. For a 10% noise level the uncertainties in strength and depth exceed 30% for both 5- and 7-sensor probes, although the latter provides a significant advantage in determining the lateral position and orientation. By comparison the 14-sensor system provides a marked advantage in the precision of all parameters, with less than 16% uncertainty in strength and depth, 2 mm uncertainty in lateral coordinates, and 3 deg in orientation. We hasten to add that these computations are for a favorable situation where the dipole is relatively shallow, i.e., when its depth is comparable to the distance separating the detection coils within a given probe. For deeper sources the uncertainties will be greater. Furthermore, this illustration is based on a simplified spherical model of the cranium where the electrical conductivity is assumed to depend on radial but not angular position (the external magnetic field pattern then being independent of the exact functional description). Nevertheless, the results shown in Table I clearly display the relative advantage of using a large array of sensors.

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Table I about here  
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### 2. Remarks on Sensory Evoked Fields

One of the principal advantages of neuromagnetic methods is the possibility of locating sources of neural activity by a relatively simple procedure (1,16). The procedure does not require knowledge of the exact shape of the head, but merely the sphere that best fits the relevant region of the head. Recently it was argued that the sphere fitting the inner surface of the skull nearest the source is most appropriate (5,17). In any event, if the source is sufficiently confined to allow it to be reasonably well modeled as an equivalent current dipole in a spherical head, the resulting pattern across the scalp of the radial component of the field is always the similar: there is one region of outward field and another of inward field. This universality is due to the fact that only the tangential component of the dipole contributes to the field outside the head - the radial component is magnetically "silent". Magnetic field lines form closed loops around the dipole, and the extrema indicate where the loops are most dense where they emerge from and enter the scalp. To determine the lateral position and depth of the current dipole, it is only necessary to locate the positions of the maximum outward and inward radial field. The dipole is located midway between these extrema, and it is oriented perpendicular to a line joining the extrema, in the sense given by the right-hand rule of electromagnetism. Its depth is determined by the ratio of the distance between the extrema to the radius of the sphere. The strength of the dipole (the current dipole moment) is proportional to the value of the maximum field and related to the depth of the dipole.

The first evidence that neural sources may be located by the positions of the field extrema was presented by Brenner et al. (18) in studies of the somatically evoked field. This work led to obvious refinements in the determination of the location, orientation and strength of a current dipole by employing a least-squares fit of the data over and near the field extrema. Okada et al. (19) used such methods to show that it is possible to identify from field patterns the cortical

representations of the digits of the hand along the Rolandic fissure. Depth determinations placed the individual source locations between 6 and 22 mm beneath the inner surface of the skull, which is an anatomically reasonable depth for sources within the fissure.

To exploit this ability to locate sources of fields, Romani et al. (20,21) studied the steady-state response to a tone whose amplitude was sinusoidally modulated at a rate of 32/sec. Mapping the field patterns for tones having different carrier frequencies showed that the depth of the source increased monotonically with frequency, with the cumulative distance across the auditory cortex within the Sylvian fissure from one source to the next varying as the logarithm of the frequency. This demonstrated the existence of a tone map across the auditory cortex which extends over a distance of about 2 cm for the range 100 - 5000 Hz. Thus, using a simple sphere model we were able to demonstrate the tonotopic organization of a portion of the human auditory cortex (Figure 1).

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Fig. 1 about here  
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It is important to emphasize that in this experiment we were able to construct reliable maps of the field external to the scalp even though the field was painstakingly measured at one place at a time, with many days of recording needed to construct the maps. This was true of steady-state fields evoked by visual and somatic stimuli, as well as auditory (for an overview see (3)). However, the story is somewhat different for transient auditory evoked fields.

The potential evoked by a long tone burst contains four major components commonly referred to as P1 (latency of about 45 ms), N1 (90 ms), P2 (160 ms) and a steady potential (SP). In their study of the N1-P2 complex, Vaughan and Ritter (21) observed a reversal of scalp potential polarity along a line corresponding to the approximate location of the Sylvian fissure, which they interpreted as evidence for the source or sources of the complex lying in the auditory cortex, oriented normal to the fissure. This interpretation was challenged because the nose was used as a reference, thus perhaps fortuitously selecting the isopotential line that passes through the nose and along the fissure as the zero line. Wolpaw and Wood (23,24), employing a multi-electrode array to take the differences of the potential, obtained a pattern of isopotentials that was independent of the reference. They too attributed the source to the auditory cortex. However, Wood and Wolpaw (24) also showed that the morphology of the waveform varies with position over the scalp. The N1 component has a longer latency over temporal areas than in the frontal areas or near the vertex. The distribution of potential for N1 also appears to differ in detail from that associated with P2, as previously reported by Simson et al. (25). Thus, the N1-P2 complex must be modeled by more than one equivalent current dipole. This is supported by the finding of McCallum and Curry (26,27) that there are three successive peaks in the N1 time-frame in measurements made on the surface of the cortex, if we choose to associate each peak with a different source.

These findings are nicely complemented by auditory evoked field studies. First, however, we should mention the convention of affixing an "m" after the symbol for an evoked potential component to indicate that we are discussing a neuromagnetic correlate of that component. Thus, "N100m" is the neuromagnetic counterpart to the potential referred to as "N100", and the "m" emphasizes that the magnetic and electric components may not in general be attributable to identical sources.

The first observations of the auditory evoked field components P100m and N100m were made over the temporal area by Reite et al. (28) for click stimuli, but Farrell et al. (29) were the first to note an anterior-posterior polarity reversal for P100m which implied that the position of its source was in or near the primary auditory cortex. Elberling et al. (30) studied responses to tone bursts of long duration and found a polarity reversal for N100m suggesting that its source lay in the same general area. Hari et al. (31) also reported a reversal of polarity of N100m and P200m, as well as the steady field (SF), where the positions of the extrema were consistent with dipole sources in or near primary auditory cortex with moments oriented perpendicular to the lateral sulcus. Thus, all of these major components of the transient auditory response, viz. P100m, N100m, P200m and SF, seem to originate in the vicinity of the auditory cortex.

As already indicated, electrical potential data suggest that N100 may well reflect the activity of more than one source. This is confirmed by a study (32) in which the amplitudes of N100m and the vertex-recorded N100 were compared as the interstimulus interval (ISI) was increased. It had

been known for some time that the N100 amplitude increases with ISI. This was confirmed by Hari and her colleagues, but it turned out that the amplitude of N100m saturated at substantially shorter ISIs than did that of N100, thus suggesting that more than one source from different regions of the brain contribute to the electrical N100. This is but one example of how the neuromagnetic and electrical measures may complement each other, since the former is primarily sensitive to sources that are tangential to the scalp while the latter is sensitive to both tangential and to radial sources. Moreover, sources at distant cerebral positions may well contribute to electrical potential differences, while this is far less likely to happen in magnetic recordings (33). However, one caveat is in order. Hari et al. measured N100 using a vertex electrode which was affected by electrical activity originating in both hemispheres. Her complementary magnetic measurements were made over the left hemisphere in all subjects. It is possible that there was an asymmetry in the effect of ISI on N100, with it saturating after longer ISIs in the right hemisphere than in the left. If confirmed in work to be conducted later, this would obviate the need to postulate sources that affect N100 but are silent with regard to their effect on N100m.

Assuming that the sources contributing to N100 are not identical to those that contribute to N100m, it is also interesting that the sources of N100m and of P200m are not in precisely the same place on the auditory cortex. Pelizzone et al. (34) showed that the latter lies significantly anterior to the source of N100m in at least two subjects. These components may differ functionally from the function of the sources of steady state responses because there is a tonal dependency of the steady state response (20,21). This raises the question of which other components show frequency dependence.

Arthur et al. (36) examined the field patterns associated with P100m, N100m, P200m and SF where the stimuli were 500-ms tone bursts of 250 and 2500 Hz. The sources of all of these components for a given subject lie within a spherical volume of 2 cm radius in the vicinity of primary auditory cortex. This study also confirmed the report of Pelizzone et al. (35) that the sources of the N1m and P2m components for tone bursts having an abrupt onset were not selectively affected by frequency. The only source that was affected by frequency was that of P100m, whose latency of 45 ms is close to the apparent latency of the steady-state response (21). Thus, for three of four subjects P100m was the only component whose source appeared to shift with stimulus frequency. However, these preliminary results will require additional study before drawing firm conclusions. Meanwhile, it is important to emphasize that one region of auditory cortex does respond differentially to tones that vary only in frequency, whereas two or more other regions may be essentially indifferent to the simple spectral composition of the stimuli and obviously have different functions.

For the present we shall ignore functions such as speech perception and comprehension since they have not yet been studied using our methods. What is more relevant is that some components of the response that appear essentially indifferent to the tonal properties of the stimulus are strongly affected by attention or other cognitive states of the subject. In fact, we shall conclude this section by asserting that the passive subject just listening to or watching stimuli is not the ideal subject to use in studies of mid-latency components of event-related fields. It suffices to say that N100 and P200 show strong effects of selective attention, and these and other components of the ERP or ERF cannot be fully understood if the subject passively listens to tones or looks at changing visual displays. We now turn to some of these effects of attention.

TABLE 1

Uncertainties in best-fitting current dipole parameters for various levels of noise, expressed as a percentage of the dipole field sensed at a field extremum. The dipole is located at a depth of 2 cm in a spherical head of 9-cm radius. For the 5- and 7-sensor systems, the probe was centered on one of the field extrema; the 14-sensor system consists of two 7-sensor probes which were centered on the two extrema.

PROBE	NOISE (%)	$\bar{Q}/Q$ (%)	$\bar{D}/D$ (%)	$\bar{x}$ (mm)	$\bar{z}$ (mm)	$\bar{PSI}$ (deg)
5-sensor	5	21	16	4.6	13.6	40
	10	42	31	6.7	20.0	64
7-sensor	5	20	15	1.2	4.0	12
	10	44	31	2.6	8.1	14
14-sensor	5	8	6	0.4	1.0	3
	10	16	11	0.8	1.9	6

**ACTIVITY OF THE AUDITORY CORTEX DURING SELECTIVE ATTENTION****1. Introduction**

The work described in this section was conducted with the collaboration of Sarah T. Curtis and it furnishes the basis for her doctoral dissertation.

Broadbent (51) likened selective attention to a bottleneck (filter) in the information processing channels of the central nervous system. Related work by Cherry (37), Moray (38) and Treisman (39), among others, used the dichotic listening paradigm to gain further insights into the mechanisms underlying selective attention. In this paradigm subjects repeat a message presented to one ear while ignoring a message presented simultaneously to the other ear. Generally, they are able to understand and remember the attended message best when the two messages are differentiated by some physical feature or features. Although subjects are aware of the presence of the ignored message, they are able to say little about its content.

The earliest bottleneck theory is similar in certain respects to the so-called single resource models of human information processing (e.g. Navon and Gopher, 52), according to which there is a limited capacity to process incoming sensory signals because there is a finite pool of an available resource to draw upon. As this pool is drawn from, less of it remains available for processing other information, regardless of its source. An alternative view is that there may be multiple resources ("channels"), and activity attended to in one of these channels need not result in the depletion of the capacity to attend to activity drawing upon other independent pools of resources (see Sperling and Doshier, 53 for an up-to-date review of the important theoretical issues associated with the notions of single and multiple resources and how these concepts may be applied to attention).

While a detailed discussion of the concept of "channels" transcends the scope of this paper, it should be pointed out that this concept is often used quite ambiguously. Thus, for example, a channel has been defined according to the sensory modality involved, the ear to which a message is delivered, the direction from which a message appears to come, and other physical features that make a particular message distinctive. These definitions of channels were usually made on an ad hoc basis. The issue was further complicated by the finding that differences in semantic content of two concurrent messages could well affect the subjects' ability to attend to one of them selectively. Thus, physical features alone need not govern the ability to keep attention focussed on one of several concurrently ongoing events.

This latter point was demonstrated by Moray (38), Treisman (40), and Treisman and Geffen (41) who showed that an ignored message may be analyzed up to the level of its semantic content, although the subject may not be aware of it. Such findings led to several alternative theories concerning the level or levels at which the filtering process ostensibly associated with attention occurs. For example, Treisman and her colleagues argued that the processing actually occurs at several stages prior to conscious perception. That is, messages are analyzed by a bank of parallel filters tuned to different physical features at an early stage in the processing sequence, and then at a higher stage based on their semantic properties, even before they reach conscious awareness. In contrast with this view, Deutsch and Deutsch (42) argued that ignored messages are first evaluated consciously but are not responded to because the competing message is being shadowed. When a message is not responded to, it is quickly forgotten. Thus, the bottleneck is due to the limited capacity of the motor system which is active during shadowing. Hence, the "filter" is not active at a level prior to conscious perception. This idea is also consistent with the observation that ignored messages may be processed to a level higher than that of simple physical features without postulating an early attenuation of signals having particular physical characteristics (Treisman, 41).

Lieberman's (54) motor theory implicated the speech producing apparatus in the perception of speech. Thus, it bears some resemblance to the theory of Deutsch and Deutsch. However, as with most motor theories of perception, it quickly became evident that Lieberman's approach would have to be modified. It may be of some interest to note that motor theories of visual perception were modified along similar lines. Thus, for example, Taylor (55) as well as Festinger, Burnham, Ono and Bamber (56) suggested that actual differences in eye movements do not underly certain illusions, but the efferent programs called up by the visual patterns do produce the illusions, whether or not the eye movements are actually executed. Similar considerations led

Stevens, (57) Neisser, (58), Hochberg (59) and Liberman (60) to assume an active participation by the perceiver as a necessary condition for what is perceived and attended to. However, this need not be a series of overt motor acts. In their view, neural programs of motor action coupled with active "covert" testing of hypotheses as to the future course of a message are essential elements of attention. While the efferent readiness theory as expressed by Festinger et al. (56) is no longer taken seriously in the field of perception (see Kaufman, 61 for a summary of the rise and fall of the theory), the similar analysis-by-synthesis notion applied to the topic of attention (Neisser, 58) still enjoys considerable respectability.

Neisser does not consider the analysis-by-synthesis theory to belong in the same class as filter theories. While it is true that this and related theories postulate the analysis of both messages up to the phonemic level during a dichotic listening task, only the shadowed message is being matched against a "speech plan" or schema (Hochberg, 59). Only then is it encoded into verbal structures, which are stored and remembered. The ignored message is forgotten because it is never encoded. The attended message is perceived because it is responded to. With this background in mind, we may now turn to consider how measures of the electrical activity of the human brain may cast light upon some of these theoretical issues.

The event related potential (ERP) can be particularly useful in determining if there is any change in the electrical activity of the brain that reflects an attenuation of physiological events related to an ignored message. Such an attenuation could represent the action of a filtering mechanism. By the same token, the enhancement of a physiological event associated with a stimulus to which attention is being paid may represent the action of an analyzing mechanism tuned to respond preferentially to that particular event. What is more, subject to some caveats to be reviewed later, the timing of either enhancement or attenuation related to attention may indicate the levels at which such filtering operations occur.

To take one obvious example, Hernandez-Peon, Scherrer and Jouvett (44) suggested that selective attention effectively gates the input from the ignored stimulus at the level of the receptor organ itself. While Naatanen (47), among others, had already raised devastating criticisms of this conclusion, it remained for Hillyard et al. (43) to put it permanently to rest. These investigators failed to find any effect of selective attention on the auditory brainstem evoked response. Such an effect would be likely to be present if the peripheral gating hypothesis were correct.

However, in a dichotic listening experiment Hillyard, Hink, Schwent and Picton (45) found that the amplitude of the N100 component of the ERP (latency 80-110 msec after stimulus onset) was larger than the corresponding component of the averaged response to the ignored stimuli. In this experiment subjects were asked to attend selectively to tone bursts presented to one ear, and press a button whenever a slightly different tone burst occurred. Meanwhile, tone bursts presented to the other ear were ignored. In subsequent studies (Schwent and Hillyard, 62; Schwent, Hillyard and Galambos, 63; 64) it was found that the magnitude of this effect of attention on N100 was greater when stimuli were presented at rapid rates and also when the stimuli were difficult to detect (Schwent et al., 49). Schwent et al. suggested that the difference in amplitude of N100 with attention reflected the selection or rejection of stimuli on the basis of their channel (ear) of entry. In a subsequent study, Schwent, Snyder and Hillyard (49) found that either the pitch cues or spatial location cues alone provided sufficient "channel separation" (p. 320) to elicit changes in the N100 component as attention is shifted among channels.

Hillyard et al. (45) also subtracted the ERPs associated with the ignored stimuli from those associated with the attended stimuli. This resulted in the generation of the so-called "negativity difference wave" (Nd) since it revealed a consistent negative shift in the baseline of the ERP beginning about 70 msec after stimulus onset (prior to the peak of N100) and extended for as long as 500 msec. The authors inferred that Nd is also a sign of early selection related to stimulus set (Broadbent, 40).

Hansen and Hillyard (65) suggested that Nd is largely endogenous in origin (also see Hillyard and Munte, 66), and its amplitude should therefore be affected by the attentional demands placed upon the subject. These demands were varied by varying the difference in frequency (pitch) between the attended and ignored tone bursts. With small differences in pitch (corresponding to a frequency difference of 50 Hz), the onset of Nd was delayed and, on the average, occurred after the peak of N100. However, when the tone bursts differed in frequency by 100 and 400 Hz, the onset occurred progressively earlier, being only about 50 msec after

stimulation for a 400 Hz difference in frequency. This was well before the peak of N100, and perhaps even prior to the onset of this component. In all cases, regardless of the difference in pitch, Nd extended well beyond N100. The partly independent onset and offset of Nd is consistent with it being an independent component, a conjecture that is supported by the greater prominence of the later phases of Nd in the frontal areas as compared with the scalp distribution of N100.

Naatanen and Mitchie (67) proposed that the modulation of the N100 described by Hillyard et al. (45) did not reflect changes in the activity of an N100 generator located in primary sensory cortex, but involved the superposition of a temporally overlapping "endogenous" component on N100. This endogenous component could coincide with the early phase of Nd. Hansen and Hillyard (65) proposed that this early portion of Nd reflects a modulation of the N100 generator, corresponding to the activation of a filtering mechanism as described in the Broadbent/Treisman model. The later phase of the negativity-difference wave was shown to have a more frontal distribution. More recently, David Wood (paper presented at Carmel conference, 1986) reported that the scalp distribution of the early phase of Nd also differs from that of N100, so it is quite possible that selective attention affects several different brain processes. These could include Nd, N100 arising in auditory cortex, and, possibly, other sources of activity in the brain that occur concomitantly with N100. In fact, Picton (68) proposed that endogenous activity in the frontal cortex may well contribute to the effect of attention on the scalp-detected N100.

One of the reasons for uncertainty as to the source or sources of the N100 phenomenon stems from the fact that most ERP studies use relatively few electrodes. This makes it virtually impossible to determine the properties of even a single current dipole source of an observed scalp potential. As pointed out by Costa Ribeiro, Williamson and Kaufman (15), if it is assumed that the source of an observed magnetic field outside the scalp can be modelled as a current dipole, then independent measurements from at least five different and strategically located positions are required to fully characterize the dipole. This requirement stems from the fact that five independent parameters characterize the dipole, namely its coordinates in three spatial dimensions, its orientation in a plane tangential to the surface, and the tangential current dipole moment. Since the electrical potential at the scalp is affected by the radial component of the dipole as well as by its tangential component, at least 6 independent parameters are required for its characterization. Since voltage is measured with respect to a reference, a minimum of 7 scalp electrodes must be appropriately placed to provide the minimum amount of information needed to characterize the source. The foregoing is true if and only if there is no noise, for if the signal-to-noise ratio is as low as 10 our ability to characterize a single dipolar source using magnetic measurements at 5 positions is seriously degraded (Costa Ribeiro, et al., 15). In this case, magnetic recordings would have to be made from many more than 5 different locations to obtain reasonable precision. There is a similar degrading effect on the ability to characterize a single equivalent current dipole using electrical measurements. Hence, many more than 7 electrodes would normally be required. The problem is compounded further when one attempts to characterize more than one source of an observed field or potential. Clearly, the usual string of a few midline electrodes is simply incapable of leading to unambiguous conclusions *vis* vis the numbers of sources underlying observed potentials. Hence, we must regard prior ERP studies that focus on effects of selective attention on N100 (and even on Nd) as being largely inconclusive about the numbers and locations of sources contributing to N100.

There have been a few serious attempts to locate the source of N100, but attention was not manipulated to determine if it affected the location of the source. Despite some controversy concerning these attempts, the work of Wood and Wolpaw (24) and of Vaughan and Ritter (69) supports the view that the N100 component of the transient auditory evoked potential has a source in or near the auditory cortex. However, as already noted, we do not know if other sources emerge during diverse states of attention.

Studies of the auditory evoked field have confirmed the conclusions of Wood and Wolpaw and of Vaughan and Ritter. The neuromagnetic counterpart to N100, which we shall label N100m because of the possibility that different sources contribute to the two morphologically similar phenomena, was first detected by Reite, Edrich, Zimmerman and Zimmerman (28). Subsequently, Elberling, Bak, Kofoed, Lebech and Saermak (30) also detected the auditory field and later Elberling et al. (70) confirmed the finding of Hari, Aittoniemi, Jarvenen, Katila and Varpula (31)

that N100m originates in or near the auditory cortex. Pellizone, Williamson and Kaufman (34) measured the field associated with a tone burst at many different places about the side of the head and also confirmed that N100m originates in the vicinity of the auditory cortex, and that its source can be resolved from the source of P200m (corresponding to the positivity in the evoked response occurring about 180 msec after stimulus onset), as well as from the sources responding to modulated tones having different carrier frequencies (Romani, Williamson and Kaufman, 20). Thus, multiple sources are present in the auditory cortex, but these sources become active with different latencies, and may well have different functional significance. For the purposes of this paper, it is important to note that the studies of N100m recounted thus far did not manipulate the attentional state of the subject. Hence, one main purpose of this paper is to determine if the source of N100m is affected by selective attention, and if other magnetic field sources contribute to any change in response associated with attention.

It is important to bear in mind that there may indeed be important differences between N100 and N100m. For example, Hari, et al.(32) found that the amplitude of N100m for a tone burst stimulus increases with the interstimulus interval (ISI), up to an ISI as long as 8 sec. However, the amplitude of N100 detected with an active electrode at Cz continues to increase with ISI as long as 16 sec in the same subjects. Hence, these authors concluded that sources contribute to N100 which do not contribute to N100m. In fact, they mention Picton's (68) conjecture that frontal sources may well contribute to the auditory N100, and such sources may not be "visible" to a neuromagnetometer because of their orientations within the skull. Therefore, an important remaining question concerns whether or not attention modulates activity of sources known to be in the sensory cortex, or if attention acts to bring in other non-specific sources. If the latter is true, then there should be no effect of attention on N100m.

Before turning to the experimental portions of this paper, it is worth noting that little effort has been devoted to the study of effects of attention on P200. Early studies (c.f. Spong Haider and Lindsley, 46) described effects of attention on both N100 and P200. Despite flaws in such studies (see Naatanen, 47 and Karlin, 48), it does appear that P200 is affected by attention in the same way as is N100. Thus, a secondary objective of this paper is to determine how P200m is affected by selective listening.

## 2. Methods

### 2.1. Procedure

The main experiment to be described below made use of a dichotic listening task which, in certain respects, was similar to that employed by Hillyard et al. (45). As in their experiment, the stimuli were tone bursts presented with fairly short ISIs to both ears. In pilot studies we found that subjects could just shadow trains of stimuli separated by about 300 ms from each other in time, and were severely handicapped in doing this with ISIs shorter than about 280 msec (the term "shadowing", as used here, will be defined later). With such short ISIs subjects claimed to be unable to perform the task of following one train of stimuli and still switch attention to the other. This need not be true of long ISIs of about 1 sec, such as those used in investigations of the transient ERP.

The acoustic stimuli were tone bursts produced by two function generators operating as voltage controlled oscillators. Voltages at different levels were provided by D/A outputs of a PDP 11/34 computer and applied to the function generators. One of the generators was set to provide a tone burst of either 1000 Hz or 1050 Hz, depending upon the applied voltage. The other was set to provide tone bursts of 3000 Hz or 3050 Hz. The lower frequency tone bursts had a repetition rate of 3 per sec, while those of higher pitch had a repetition rate of 3.5 Hz. The duration of each tone burst was 100 msec, and they were separated by periods of silence.

The outputs of the two function generators were applied separately to each of the two transducers of a plastic earphone set, similar to those used on some airlines. However, the transducers were enclosed in a mu metal cylinder (to prevent any magnetic stimulus artifacts) and kept at least 60 cm from each earpiece. The acoustic stimuli were conveyed to the ears by a pair of plastic tubes. Thus, one ear received tones of either 1050 or 1000 Hz, while the other ear received tones of either 3050 or 3000 Hz. Prior to the beginning of each session the subject listened to the two series of stimuli and instructed the experimenter to adjust the loudness of one until it appeared

to match that of the other. Except in the case of one control experiment, in which the loudness of one ear's stimulus was reduced by 20 dB, the intensities of both stimuli were at an approximate level of 70 dB SPL.

One of the main differences between this procedure and that employed by Hillyard et al. is that our stimuli were presented periodically while their ISIs were randomized. Still another difference relates to the task itself. In their procedure target stimuli in one channel were to be detected amongst other stimuli which had to be monitored. It was assumed that listening for relatively rarely occurring target stimuli in one ear's train of stimuli sufficed to keep attention maintained toward that ear. In the present study the stimuli to either ear were presented in a pseudorandom sequence. That is, tones of lower and higher pitch (say the 1000 Hz tone burst and the 1050 Hz tone burst presented with a 3/sec repetition rate) had an equal probability of occurrence. However, this random sequence had a finite length and was then repeated. The average length of such a sequence was about 30 tone bursts. The subject was instructed to listen to this sequence and determine how many tone bursts occurred before the entire sequence was repeated. At the same time the 3000 Hz and 3050 Hz stimuli were presented in an entirely independent pseudorandom sequence at a repetition rate of 3.5/sec. While attending to the 3/sec stimulus, the subject ignored the 3.5/sec stimulus, and vice versa. After one such run during which responses were averaged for 164 sec there were 492 presentations of the 3/sec stimulus and 574 presentations of the 3.5/sec stimulus. After the run the subject was asked to tell the experimenter the total number of high and low pitch tones in the repeating pattern. Formal data collection did not begin until the subject was able to perform this task with an accuracy approaching 95%. On the next run the subject was told to switch his attention to the previously ignored ear. Thus, the stimulus from one run to the next was essentially the same, except that the instruction to attend to one ear or the other was varied. Introspective reports by the subjects and by the experimenters who listened to the stimuli suggested that attention was sharply focussed on the train of stimuli that was being followed to determine the length of its pattern, while the listener was completely unaware of the pattern of the ignored stimulus. The experience was not unlike that of shadowing a spoken message presented to one ear while ignoring a message presented to the other ear during the classic dichotic listening task.

The activity of the brain was monitored on only one side of the head during a run. Thus, for example, the subject lay on his left side with the 3/sec stimulus presented to his left ear and the 3.5/sec stimulus to his right ear. The magnetic sensing system was positioned over the right side of the subject's head where it was kept while the subject attended to the stimulus to the left ear, and also when he ignored that stimulus and attended instead to the stimulus to the right ear. The sensors were then moved to another position on the right side of the head and the entire procedure repeated (using independently selected pseudorandom sequences) several times. The 3/sec stimulus was always presented to the ear contralateral to the side of the head being examined. Then the subject was moved so that the sensors could be placed over the left side of the head where the procedure was once again repeated many times, with attention deployed first to one ear and then to the other. Thus, for each position of the sensors there were two conditions: attend 3/sec and attend 3.5/sec. Two to six runs were recorded at each position, with the larger number of runs conducted with the sensors placed at locations over the scalp that provided the strongest responses of the brain.

In an additional condition, subjects were presented with the 1000 Hz tone bursts and the ISI was increased and made to vary at random from 1000 to 1500 msec, and the subject was instructed to listen passively to the tone bursts. This permitted the collection of classic transient ERPs so that we could check on whether or not known components in the ERP (N100m and P200m in particular) corresponded to deflections in the waveforms of the responses of the main experiment.

As intimated earlier, in another control experiment the stimuli were made markedly different in loudness, with one ear's stimulus attenuated 20 dB below the level at which it appeared to match the other stimulus in loudness. Then the subject attended to either the louder or softer of the two stimuli to determine if any of the effects to be reported below were possibly due to uncontrolled differences in loudness of the stimuli.

Finally, the outputs of the two function generators were applied to one ear piece, thus requiring the subject to follow one of the two trains when both of them were presented to but one

ear. In this case pitch alone was the cue used by the subject to keep the two trains separated in attention.

In addition to all of the foregoing conditions, the same stimuli were presented to one subject via two piezoelectric loudspeakers. In one series of trials the speakers were positioned so that one was closer to one ear, and the other closer to the other ear. Thus, although the tone bursts from one speaker were more intense at one ear than at the other, both series of tones could be heard by both ears.

## 2.2. Instrumentation

The ERF (event related field) has proven to be extremely useful in determining the location within the brain of sources of externally measured magnetic fields. These fields arise from the intracellular flow of ionic currents and emerge and reenter the head without any distortion being introduced by intervening tissues such as the skull, cerebrospinal fluids, etc. Consequently, using the equivalent current dipole as the model for the source, it is possible to determine the position in three dimensions of the source, its orientation in the plane tangential to the surface, and its tangential current dipole moment (intensity), without detailed knowledge of the variations in conductivity between the source and the surface of the head, so long as the concentric shell model for the cranium is adequate. The field pattern has one region of outward field and another of inward field. The lateral position of the equivalent current dipole used to model the source is midway between the two field extrema, with the dipole pointing at right angles to the line joining the extrema, in the sense of the right hand rule of electromagnetism. The depth of the source beneath the scalp is determined by the ratio of the distance between the extrema to the radius of the head (Cuffin and Cohen, 71; Williamson and Kaufman, 2). Neuromagnetic techniques have the capability in favorable circumstances of high precision in source localization. For example, in the first demonstration of the tonotopic organization of portions of the human auditory cortex (Romani, Williamson and Kaufman, 20; 21), it was found that cortical regions responding to tones an octave apart could be resolved with an accuracy of 2 or 3 mm along the floor of the lateral sulcus.

The strength (current dipole moment) of the source is actually the phenomenon of greatest interest. Let us consider for example the hypothetical case of a potential difference between two electrodes related to a particular event in time. This potential difference can be assumed to be large when the subject pays attention to the event, and small when the subject ignores the event because he is paying attention to something else. It is impossible in the absence of source localization to determine from this kind of data if the effect of attention is to enhance activity of a particular neural source, if the location of the active neural tissue during attention differs from its location when the event is being ignored, or if the effect of attention is due to the contribution of other sources. However, a direct measurement of the current dipole moment of the source, as revealed by neuromagnetic techniques, could clarify such issues. Thus, the method of magnetic recording seems ideal for determining if sources within the auditory cortex are affected by attention, or if all or most of the variance in N100m and P200m due to attention must be ascribed to sources that lie elsewhere in the brain.

The study of the brain's magnetic field requires the use of extremely sensitive instruments. Today these are based on the superconducting quantum interference device (SQUID). For a review of the principles underlying such devices and how they are employed in neuromagnetic measurements see Romani, Williamson and Kaufman (16). In the present experiment we employed a system composed of five sensors, each monitoring the field with a detection coil in the form of a second-order gradiometer (Williamson et al., 11). Each detection coil consists of three coils, the center one having twice as many turns as the end coils and wound in the opposite direction. The diameter of the coils is 1.5 cm, and the baseline separating the end coils from the center one is 4 cm. Each of the five detection coils is magnetically coupled to a dcSQUID, and all of the superconducting components are immersed in liquid helium within a fiberglass dewar. Four additional SQUID sensors are enclosed within the same dewar to monitor components of the ambient field and the gradient of the field along the dewar's axis. These four references are suitably attenuated and subtracted from each of the five signals to improve the signal-to-noise.

The five detection coils of the signal channels are arranged in the pattern of a cross, with the bottoms of the four outer coils separated from the central one by 2 cm. The tops of the outer coils

are tipped outward from the axis of the center one by  $10^\circ$ , so that all the coils point to a common position 9 cm beneath the bottom of the dewar. This allows the instrument to measure the radial field external to the head from 5 positions at once. Calibration studies demonstrated that there is less than 1% "cross-talk" (mutual inductance) among these channels. For more details see Williamson, Pelizzone, Okada, Kaufman, Crum and Marsden (11).

The output of the SQUID electronics is a voltage that is proportional to the field linking the bottommost (pickup) coil of its gradiometer. With the source closer to the coil than the 4 cm baseline of the gradiometer, the effect of its field on the higher gradiometer coils is negligible. Hence, the voltage output of a SQUID to a nearby cortical source is a measure of the average field linking the pickup coil. The outputs of the SQUID electronic units were applied to analog comb filters to attenuate noise at 60 Hz and at 180 Hz. Then the outputs of the five signal channels and four references channels were applied to bandpass filters set to pass frequencies between 1 and 45 Hz, with 48 dB/octave rolloffs. Following subtraction of the attenuated references from each of the signal channels, the remaining five signals were applied to the A/D converter of the PDP 11/34 computer for analysis (see below).

The dewar is mounted in a specially designed holder that permits the bottom of its tail section to move in any direction while pointing to a fixed point in space. With the center of the head of the subject placed at the same point, it is possible to move the dewar so that its coils would be at known positions with respect to landmarks on the head. Vacuum pillows placed under the subject's head were evacuated to provide a stable platform to insure that the subject maintained the set position throughout a run. Since the head is not actually spherical, after the dewar was positioned over a desired location it could be moved toward the scalp to place it as close as possible to maximize the signal strength.

Landmarks on the head were the ear canal, the outer canthus of the eye, and the vertex of the subject's head. These landmarks were used in positioning a nylon bathing cap on the subject's head. Marks on the cap indicated the positions with which the tail section of the dewar was to be aligned. The head was placed so that it barely touched the bottom surface of the tail section of the dewar. This made it possible to record fields with all of the pickup coils at about the same distance from the scalp. Since 5 measurements were made at each dewar position, and since the dewar was positioned over 6 to 10 different locations on each side of the head, the field was sampled at 30 to 50 different locations over each hemisphere.

A substantial number of pilot studies were conducted prior to the formal experiment to be described below. One purpose of these pilot studies was to determine the general locations of the stronger stimulus-related fields relative to the major landmarks of the head. We saw no signs whatever of fields which could have frontal or occipital sources. All of the data pointed to sources near the temporal lobe of the brain. Hence, most of the positions used to sample the field were chosen to permit detection of sources in that region. However, it is also important to note that in the formal experiment itself, after examining the way in which the field strength varied with position across the head, we asked subjects to return for follow-up measurements to be sure that we had fully explored the field pattern external to the scalp.

### 2.3. Analysis

Since the repetition rates of 3/sec and 3.5/sec are not integer multiples of each other, it is only the 6th harmonic of the latter rate and the 7th of the former that are coherent. Hence, any activity of the brain at 3 Hz (the fundamental frequency component of the 3/sec repetition rate) or its higher harmonics up to the 7th would be due strictly to the 3/sec stimulus, while activity at 3.5 Hz and its next five harmonics would be due to the 3.5/sec stimulus. This makes it possible to detect average responses due to one stimulus without those responses being contaminated by responses to some other concurrently presented stimulus.

The averaging computer can be conceptualized as a comb filter. Imagine that a periodic stimulus is presented every 333 msec (3 Hz). The sweep of the computer is set to coincide with the 333 msec ISI or at some integral multiple of that ISI. Activity that recurs at 3 Hz, 6 Hz, 9 Hz, and so on will always have the same phase relationship to the stimulus event, regardless of how many sweeps are added to obtain the average. However, activity that recurs every 286 msec (corresponding to a fundamental frequency of 3.5 Hz) will change phase from sweep to sweep as averaging to recover activity at 3 Hz and its harmonics is underway. As the averaging time is

increased, activity that is not harmonically related to the fundamental stimulus frequency will contribute to the average in proportion to the square root of the number of sweeps entering into the average. By contrast, activity at 3 Hz and its harmonics will increase arithmetically with the number of sweeps. By the same token, when one averages with a sweep duration of 286 msec then activity at 3.5 Hz and its harmonics may be recovered independently from the same overall brain activity from which the activity at 3 Hz and its harmonics were previously recovered. This technique is suitable for the present purpose, since it allows us to recover signals due to two different stimuli from the same region of the brain.

In the present application we did not perform simple signal averaging in the time domain but worked directly in the frequency domain instead. Thus, an FFT was performed on each 4 sec segment of magnetic field activity from each channel. Activity at 3 Hz and its harmonics (up to the fifth harmonic) was extracted, as was activity at 3.5 Hz and its harmonics up to its fifth harmonic. These Fourier components were averaged over many such 4 sec segments and then summed to synthesize waveforms corresponding to the responses to the stimuli presented at two different repetition rates. This procedure allowed us to examine effects of attention on the Fourier components of the quasi steady-state responses as well as on the conventional negative and positive peaks. This enabled us to determine the degree to which harmonics of one of the fundamentals contributed to the response to the stimulus presented at the other repetition rate. It can be shown that this procedure is essentially equivalent to averaging using two different sweep durations corresponding to periods that are not harmonically related to each other. In other words, the resulting waveforms are the same as would be obtained by independently computing responses to stimuli presented during the same period of time.

When tone bursts were presented at random intervals ranging from 1000 to 1500 msec, the average transient responses from all 5 channels were computed using the standard signal averaging algorithm. The responses contain prominent and easily identified peaks that apparently correspond to the classic N100 and P200 components of the ERP. These responses are described in the Results section. After the experiments were completed the experimenter identified these peaks and their amplitudes in femtotesla (fT - a unit of magnetic induction) were plotted as a function of position on the scalp. A computer program based on a program known as GRID 3 was employed to fit the data obtained at many different positions about the scalp by contours representing fields of equal strength. These contour plots were made in rectangular coordinates in which distance between the ear canal and the outer canthus of the eye is represented along the X-axis, and vertical distance from this line toward the midline is represented along the Y-axis. The interpolation and smoothing routines incorporated in the program made it possible to estimate the coordinates associated with the two field extrema in isofield contour plots of data representing the amplitudes of the fields occurring at the peaks of N100m and of P200m. Knowing these coordinates and the amplitudes at these coordinates, we then measured the actual distances between them on the scalps of our subjects. We also measured the diameters of their heads in several directions, and computed a mean radius for each of them. This information sufficed for us to define the characteristics of the equivalent current dipole source that would produce the best fitting dipolar field pattern. These characteristics include the location of the tangential current dipole and its orientation as well as its strength.

Essentially the same procedures were applied to the data obtained using the 3/sec and 3.5/sec repetition rate stimuli. Typically, responses to stimuli at these repetition rates contained two prominent peaks that correspond to what we have labelled N100m and P200m. Contour maps were made and sources computed for these peaks. In addition, similar maps were made and computations performed for the fundamental, second and third harmonic frequency components of these responses.

While the position of source within the head is determined by the locations of the field extrema, the strength of the source is given by its distance from the sensor and the amplitude of its field. More specifically, the current dipole moment associated with the excitation of a neuron is the integral of the intracellular current along the length of the neuronal process. Assuming that the process is the apical dendrite of a pyramidal cell, it has been estimated that its total current dipole moment could be on the order of  $3 \times 10^{-15}$  A-m (Williamson and Kaufman, 1987). However, the field associated with this current would be too weak to detect from any appreciable distance. It has been estimated that the fields of approximately 30,000 such elementary sources would have to

summate to be detected outside the scalp. In this case the (tangential) current dipole moment would be about 10 nA-m, although observed fields have been an order of magnitude greater in strength, and perhaps a factor of five weaker. Thus, we envision the equivalent current dipole as standing for a large population of neurons, but one that occupies a small space as compared to the distance from which the net field of that population is being observed. For a detailed review of the physical background to this, and for the equations relating field measurements to source strength under various sets of assumptions, see Tripp (72) and Williamson and Kaufman (2).

Most of the useful information in the isofield contour maps is in the vicinity of the field extrema. Thus, for example, shifts in the locations of these extrema signify changes in the position and orientation of the underlying source. Data collected in the vicinity of the extrema readily indicate such changes. If the position or orientation of the source in the tangential plane does not change significantly, then changes in the magnitudes of the extrema signify a change in the amount of underlying neural activity. Since we obtained many independent measurements of the field in the vicinity of the extrema, it was possible to examine the statistical significance of the effects of various treatments on the strengths of the fields and, by inference, on the amount of underlying neural activity. Since some of the measurements were repetitions of prior measurements taken at the same positions, they were averaged to give us a single measurement per position. In all, we used 5 measurements from the vicinities of each of the observed extrema over both hemispheres, making a total of 20 measurements per subject in an ANOVA. This enabled us to examine the effects of instruction (to attend or ignore), the repetition rates of the stimuli, the components of the response (N100m and P200m), the channels used to detect the fields (position), the hemisphere over which the measurements were taken, and whether the sensors were positioned over the anterior or posterior field extrema.

#### 2.4. Subjects

Three subjects were employed in this experiment, two male (DS and SV) and one female (JE). The subjects ranged from 22 to 26 years of age. All were right handed and had normal hearing. Partial data were obtained from another female subject (CB).

#### 3. Results

Responses to stimuli presented at a 3/sec repetition rate and recorded from the left hemisphere of one of the three subjects are shown in Figure 2. The dark waveforms are responses obtained while the subject attended to the stimuli, while the dashed lines were responses obtained at the same positions at the scalp but when the stimuli were being ignored. The responses obtained during attention are clearly larger in amplitude, and contain two pronounced peaks, one at about 100 msec and the other about 225 msec after stimulus onset. The waveforms on the right side of the Figure show similar results obtained when the stimuli were presented at a repetition rate of 3.5 Hz.

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Insert Figure 2 About Here

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The first peak in the waveforms of Figure 2 occurs at about the same times as does the N100m component of the the transient AEF. However, the second peak occurs about 25 to 50 msec earlier than the P200m. Because of this as well as the difference in ISI between the periodically presented stimuli of this experiment and that used in the typical transient response study, the peaks found in this experiment may not have the same sources as do the more frequently studied N100m and P200m. Therefore, we recorded transient AEFs from two of our subjects using the same tone bursts as those employed in the main experiment. The main difference is that the ISIs were randomized within the range of from 1000 to 1500 msec, and the subjects were given no special instructions except that they were to simply listen to the tone bursts. Waveforms showing the transient magnetic responses obtained from one of the subjects are shown in Figure 3. The polarity reversal exhibited by the superimposed waveforms indicate that they were recorded from near opposed field extrema. These responses exhibit clear N100m and P200m components.

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Insert Figure 3 About Here

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Isofield contour plots were made for the peaks of the N100m and P200m components of the transient responses. Sample plots are shown in Figure 4. These were compared with similar plots made for the peaks of the responses using the quasi steady state stimuli (3/sec and 3.5/sec repetition rates). Within the error of positioning the dewar over the head (about 1 cm in this experiment), it must be concluded that the locations of the sources of N100m and of P200m cannot be distinguished from the locations of the sources of the peaks obtained using the short ISIs of our main experiment. Therefore, we shall refer to these peaks as N100m and P200m as well.

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Insert Figure 4 About Here

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An isofield contour plot made for N100m obtained while one subject (SV) was attending to the 3/sec stimulus is shown in Figure 5A. A similar plot, based on data obtained when the same subject was ignoring the stimuli is shown in Figure 5B. These particular data were selected because they demonstrate that for at least one subject there seems to be a clear exogenous response at N100m, (and also at P200m, which is not shown in the form of an isocontour plot here) despite the fact that its amplitudes at the extrema are smaller than those obtained when the subject was attending to the stimuli. This was not always the case, since responses of the other two subjects to the ignored stimuli were quite close to the background noise level, and this made it difficult to construct contour plots for the purpose of comparing the locations of their sources with the locations of the sources of the responses to the attended stimuli. However, for subject DS it is clear that the sources of the responses to the ignored stimuli were in the same locations as the sources of the responses to the stimuli to which attention was being paid.

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Insert Figures 5a,b About Here

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As described in the Methods section, an ANOVA was performed using the field amplitudes measured at 20 different positions outside the scalps of all 3 subjects. The positions were those at which responses significantly greater than background noise were measured. Since the ANOVA included a test for the significance of differences in the amplitudes of N100m and P200m, two different amplitudes at each of the 20 positions furnished the data for analysis.

No significant differences were found between the amplitudes of N100m and P200m. Moreover, we found no consistent hemispheric differences. There were significant differences among the amplitudes of the peaks measured at different positions, but this is to be expected as the different positions were at different distances from the field extrema. The most important finding was that the effect of instruction to attend to a stimulus (and, by implication, ignore the alternative stimulus) was significant with  $p = .028$ .

We also compared the first three harmonics of the responses of subject CB after their waveforms were analyzed by means of an FFT. There was no significant effect of instructions on the 2nd and 3rd harmonics. The effect of attention was fully accounted for by changes in the amplitude of the fundamental component of the response. Since the fundamental components (3 Hz and 3.5 Hz) are not harmonics of each other, the effect of attention on a response at one frequency could not account in any way for the effect observed on a response at the other frequency.

In a control experiment one of the two stimuli was reduced in intensity by 20 dB. This had no effect on the amplitude of the response, whether it was a response obtained while the subject was paying attention to the stimulus or if the stimulus was being ignored.

In another control experiment the stimuli were presented monaurally to two of the subjects (JE and SV) so that they could be heard by only one ear, thereby removing the cue of difference in perceived spatial locations of the two stimuli. Apparently, the remaining difference in stimulus pitch was sufficient to allow the subject to focus attention on one of the stimuli, as the effect of attention on the response was virtually the same as it was in the dichotic listening experiment.

In addition to comparing the field strengths obtained when the subject paid attention to the stimuli with those obtained when the stimuli were ignored, the positions of their equivalent dipole

sources were computed from the locations of the extrema on the subjects' scalps. In all cases the sources of both N100m and P200m were located in or near the auditory cortex. This was consistent with the location of the point on the scalp that bisected the field extrema, and also with the depths of the sources. Thus while attending to the stimulus the source associated with N100m evoked by the 3/sec stimulus was 2.4 cm beneath the left scalp and 3.1 cm beneath the right scalp of subject DS. The source of P200m of DS for the same stimulus was 2.6 cm deep on the left side and 2.3 cm on the right side. The tangential current dipole moments for these same sources were computed to be 4.6, 5.5, 4.5 and 2.0 nA-m respectively. The depths of these same components when the stimuli were ignored were found to be identical to when they were attended to. However, for N100m the current dipole moment was 3.7 nA-m in the left hemisphere and 3.8 nA-m in the right. The moments associated with P200m when the stimuli were ignored were 2.5 nA-m on the left side and 1.4 nA-m on the right. The N100m evoked by the 3.5/sec stimulus had a source in the left hemisphere which was at a depth computed to be 3.6 cm, and one in the left hemisphere at a depth of 2.3 cm. When attention was paid to this stimulus, the current dipole moment characterizing the source in the left hemisphere was 4.4 nA-m, and the source in the right hemisphere had a moment of 1.6 nA-m. When these same stimuli were ignored the locations of the two sources did not change, but the current dipole moment was lower, being 3.6 nA-m in the left hemisphere and 0.8 nA-m in the right. Comparable results were obtained with the other subjects. Thus, N100m in subject SV was at a depth of 2.6 cm on the left and 3.3 cm on the right. While the position of the source was unchanged when the 3/sec stimulus was ignored, the current dipole moment was lowered from 2.9 nA-m on the left to a value of 1.9 nA-m, and from 3.7 nA-m to 2.7 nA-m on the right. Similar results were obtained for the 3.5/sec stimulus. It is noteworthy that the depth of the source of the N100m component of the transient response measured in this same subject was 2.6 cm in the left hemisphere (the same as the quasi steady state component), but its current dipole moment was 12 nA-m. In subject JS the depths of the sources of the N100m and P200m components were 2.6 and 3.3 cm respectively on the left, and 3.6 and 3.3 cm on the right. The depths of the sources of these same components evoked by the 3.5/sec stimulus differed slightly from the foregoing. For N100m the depth on the left was 4.0 cm and on the right it was 3.6 cm. The depth of the source of the N100m component of the transient response obtained over the left hemisphere was also 2.6 cm. The current dipole moment of the latter source was 25 nA-m, which is much greater than those obtained for the 3/sec and 3.5/sec stimuli. The latter ranged from 2.5 to 7.2 nA-m, but those associated with the ignored stimuli were all weaker than those obtained when the subject paid attention to comparable stimuli. These depths are consistent with the sources lying in a sulcus. Moreover, since the source position did not change when the subject ignored a stimulus rather than paid attention to it, it must be concluded that no nearby additional source was activated during attention. Moreover, measurements were taken from positions that sampled most of the scalp, and there was no indication at all of the presence of additional sources.

#### 4. Conclusions

The main conclusion to be drawn from these results is that activity originating in the auditory cortex is modulated by attention. There is no sign at all of the presence of other non-specific sources that contribute to the auditory N100m and P200m. While we cannot rule out the possibility that other non-specific sources may contribute to the effect of attention on the electrical N100 and P200, the magnitude of our effect suggests that such additional sources would add very little to the modality specific effect of attention.

In view of other studies cited above, it is clear that N100m and P200m originate in the auditory cortex, and their sources are quite close to the primary receiving area. The fact that tissue in such close proximity to regions of very early cortical processing of acoustic information is affected by attention provides us with an important problem for future consideration. This result suggests at least two possible hypotheses. The first of these is that the "filter" is located prior to conscious perception, and is activated when a task is performed with a set to select from among different stimuli. The second possibility is that the selection is first completed at some much later stage of processing, and through some feedback loop this results in the attenuation of signal due to stimuli that are being ignored. This would lead to the prediction that if responses could be recovered without signal averaging, then the first responses to ignored stimuli would be as strong as those to attended stimuli. However, as further stimuli are provided, responses to those that are ignored will become increasingly attenuated. Hence, we cannot completely rule out a theory

which places the filtering operation at some later stage. Since we will be installing a magnetically shielded room in a very short time, it will be possible to obtain responses with very little signal averaging. Hence, it should be possible to test this hypothesis. Even so, on the average, the relatively attenuated response to ignored stimuli is reflected in activity of the auditory cortex. It is also important to note that P200m displays the same type of response change as does N100m. It remains a problem as to whether or not the separated source of P200m has some specialized functions of its own.

## MODULATION OF ACTIVITY OF VISUAL CORTEX BY ATTENTION

### 1. Background

The work described in this section was conducted with the collaboration of Bruce Luber.

As in the case of auditory attention, this research is designed to determine if changes in the ERF due to selective visual attention are due to modulation of specific sensory areas, or if they are due to differential activity of non-specific areas of the brain. Thus, in this ongoing study we inquire if activity of visual cortex is differentially affected by selective attention to events in visual space.

### 2. Method

Since our concern here is with the visual cortex, mapping of the field external to the head was done in the occipital and parietal regions. The subject lay prone on a bed and looked through an aperture down into a mirror which reflected the image on the screen of a display oscilloscope to his eyes. This made it possible to move the neuromagnetic probe around the occipital and parietal regions of the head while the subject fixated a mark on the screen.

The stimuli were two bar gratings placed one above the other on one side of a screen of uniform luminance. Each grating pattern subtended 3 deg horizontally and 2 deg vertically, with a 0.5-deg strip of uniform luminance separating them. The fixation point was at the center of the screen, on the midline of the strip and 0.5 deg to the side of the nearest edges of the gratings. The mean luminance of the grating matched the background luminance of the screen. The gratings were generated using an Inisfree Picasso Image Generator driven by a PDP 11/34 computer. One of the gratings had a spatial frequency which was alternated between 1.25 c/deg and 2.50 c/deg. The other grating had a spatial frequency which alternated between 3.5 and 7.0 c/deg. The two spatial frequencies in one of the gratings were presented in random order at a presentation rate of 3/sec. At the same time the other two spatial frequencies in the second quadrant of the display were presented in random order at a rate of 2.75/sec. Each grating in the former sequence was presented for 200 msec, and those in the latter sequence for 250 msec.

Thus far the basic procedure is analogous to that used in the auditory experiment. None of the first 10 harmonics of 3/sec and 2.75/sec coincide, so the averaging computer can accept the band-limited signal and selectively analyze responses at these two repetition rates. However, following the suggestion of Dr. Risto Ilmoniemi, we modified the procedure slightly. Rather than employ a pseudo-random sequence where the length of the pattern prior to its repetition had to be detected, the pattern in one quadrant had one of two possible spatial frequencies which were always selected at random. However, the trial simply stopped after a randomly selected interval of time which could range from 4 to 40 sec. The subject never knew whether a trial would be long or short. His only instruction was that he had to keep track of one of the two stimuli so that when the train stopped he could tell the experimenter the spatial frequencies of the four or five patterns immediately preceding cessation of the trial. The average responses to the attended and ignored patterns were accumulated and then averaged together subsequently. This was to assure that at least 600 events entered a particular average.

This procedure has some advantages over the one we had used previously. The most obvious of these is that the strategy used by the subject in performing the task does not change so markedly as it might when performing the original auditory task. The subject must keep track of the stimulus to give an accurate answer to the question concerning the preceding four or five stimuli in a given quadrant. In fact, we have data from one male subject who was unable to perform the task, and his responses failed to show differentiation related to the instruction to attend to one stimulus and ignore the other.

### 3. Results

The results of the vision experiment are incomplete. Thus far we have completed full sets of measurements on only two subjects. However, qualitatively the two sets of data are alike, and because the findings reveal a significant feature of these subjects' attentional effect, we report the results here. Also, we had one subject who showed no effect of instructions to attend, but he did not provide any behavioral evidence that he was able to perform the task.

Figure 6 is an isofield contour plot for the 150-msec component of the response that was in step with the attended 3.5/sec 7.5 c/deg stimulus presented at a rate of 3/sec. Figure 6A displays the response for attended stimuli in the upper right quadrant of the visual field. The classic description of the cortical representation of the visual field, the cruciform model, indicates that if fixation was as instructed the stimulus had its first cortical effect in the floor of the calcarine fissure and adjacent wall of the longitudinal fissure of the left hemisphere. Indeed, the current dipole that best explains the pattern in the upper panels of Figure 6 is tipped slightly toward the upper right, which is consistent with this region of cortical excitation if the balance of intracellular current flows toward the surface of the cortex.

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 Fig. 6 About Here  
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Figure 6C depicts responses for attended stimuli in the lower right visual field. The corresponding current dipole is more horizontal, indicating a different distribution of cortical activity than for stimuli in the upper right visual field. However, we would expect from the cruciform model that the dipole would be oriented toward the lower right, indicating excitation across the ceiling of the calcarine fissure and adjacent longitudinal fissure. The data do not support this picture.

When the same stimuli are ignored (Figures 6B,D) there is a significant reduction in dipole source strengths for gratings presented in both the upper and lower right visual field. This establishes the principle that activity can be affected by attention in the corresponding different regions of visual cortex. There is no significant change in source position or orientation. Similar results are seen in the responses to stimuli presented at 2.75/sec.

The 85-ms component, as well, displays marked attentional effects. While the corresponding sources evoked by upper right and lower right presentations in general behave quite similarly to those for the 150-ms component, there are also some differences. In fact, there appears to be a shift in the orientation of the current dipole when the stimulus is ignored rather than attended to. We are currently exploring ways in which shifting of eye fixation may affect these results. The results of this ongoing work will be the subject of a future publication.

### PUBLICATIONS IN TECHNICAL JOURNALS

Kaufman, L. and Williamson, S.J., Recent Developments in Neuromagnetism, Third International Evoked Potentials Symposium, West Berlin, September, 1986 (to be published).

Williamson, S. J. and Kaufman, L., Neuromagnetism: A Window onto the Brain. Submitted for publication in ELAN.

Kaufman, L. and Williamson, S.J., The Neuromagnetic Field., in Bodis-Wollner, I. and Cracco, R.Q. (Eds.), Frontiers of Clinical Neuroscience, Vol. 3, New York, Alan R. Liss, 1986.

### CONFERENCES ATTENDED

Third International Evoked Potentials /symposium, West Berlin, September 28 - October 1, 1986. (LK and SJW).(paper presented)

Winter Conference on Brain Research, Keystone, CO., Jan. 25 - 30, 1986 (SJW).

Neuroscience Meeting, Washington DC, November 1986 (SJW, LK, BS, RI, SC, BL) (one paper and one poster presented)

**Invited talk at IEEE Conference, Fort Worth, TX, November 8 - 10, 1986.**

**Consultation at AAMRL, WPAFB, Dayton, Ohio, December 1 - 4, 1986 (LK).**

**Collaborative work underway throughout the year with Dr. E. Flynn and colleagues at Los Alamos National Laboratory (SJW).**

**PROFESSIONAL PERSONNEL**

**Dr. Risto Ilmoniemi Dr. Barry Schwartz Dr. Jia-Zhu Wang Dr. Samuel J. Williamson Dr. LLOYD Kaufman**

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## FIGURE LEGENDS

Figure 1. Constant field contours across the right hemisphere for the neuromagnetic response to clicks presented at 32 Hz. Values indicate the strength of the field perpendicular to the scalp in femtotesla, with positive values for the outwardly directed field. The orientation of the underlying source is represented by the arrow. The origin of the coordinate system is the ear canal, with the horizontal axis directed toward the corner of the eye (at +9), and vertical position measured along the scalp perpendicular to this axis. The location of the center of the arrow in this system represents the lateral position of the source, and the depth is related to the separation between the field extrema.

Figure 2. Auditory evoked fields obtained with a 5-sensor probe placed over the anterior extremum of the left hemisphere of subject DS, averaged at 3/sec (left column) and 3.5/sec (right column). Solid lines are responses when the subject attends to the 3/sec train, and dashed lines are for the 3.5/sec train. Each trace corresponds to 500 repetitions for the 3/Hz train and includes the fundamental and 4 harmonics.

Figure 3. Transient auditory evoked fields illustrating the reversal in polarity of the field when the two recordings, which are shown as superimposed, are made from near the opposed extremas for N100m and P200m.

Figure 4. Isofield plot for N100m obtained from transient responses.

Figure 5. A) Isofield plot made for "N100m" when subject SV attended to 3/sec stimulus, and B), when the stimulus was ignored.

Figure 6. Magnetic field patterns over the occipital area of a subject for the 150 ms component evoked by visual presentation at 3/sec of gratings randomly selected to have spatial frequencies of 3.5 or 7.0 c/deg. The stimuli were presented in the upper right visual field (A,B) and lower right visual field (C,D). Responses to attended stimuli are shown in A and C and to ignored stimuli in B and D. Arrows show the positions of equivalent current dipole sources as determined by the positive and negative field extrema. Horizontal distances across the scalp from the midline and vertical distances from the inion are indicated in centimeters. Isofield contours are given at 10 fT intervals, which is comparable to the noise level in the measurements.

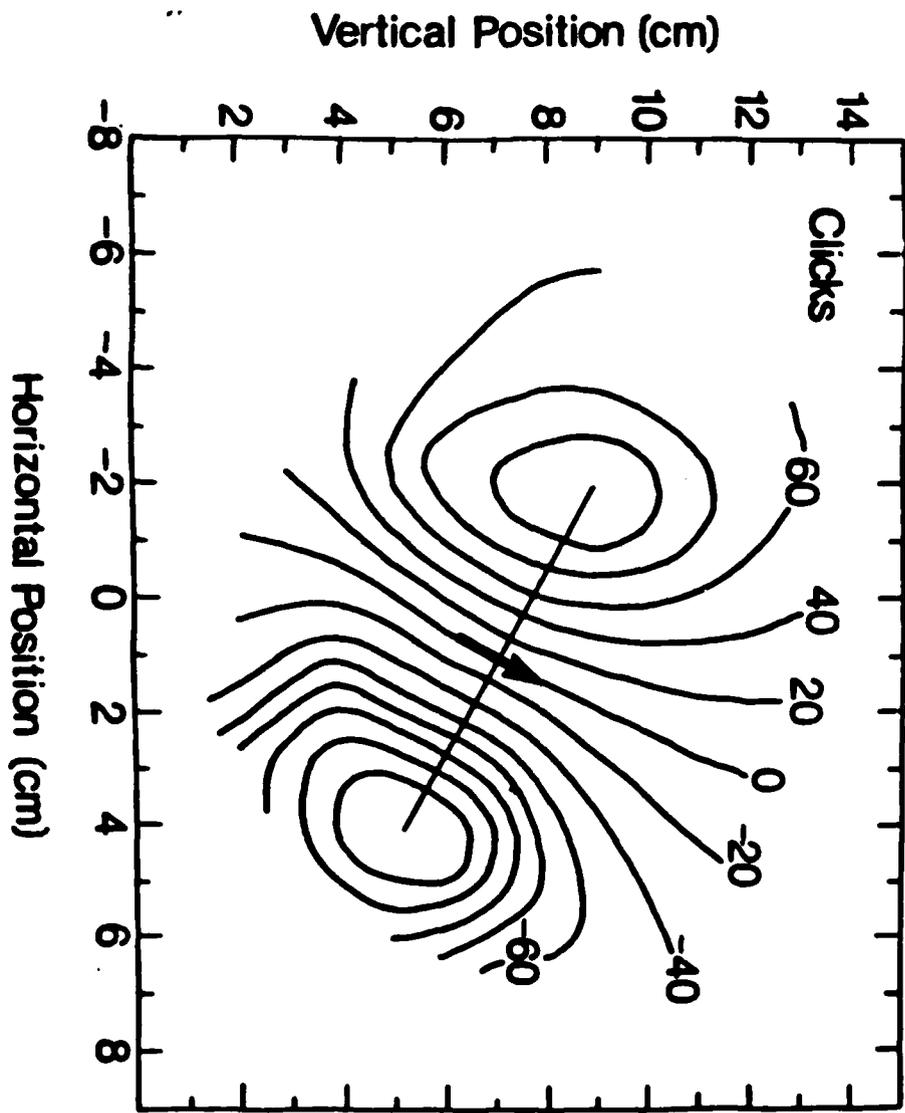


Figure 1

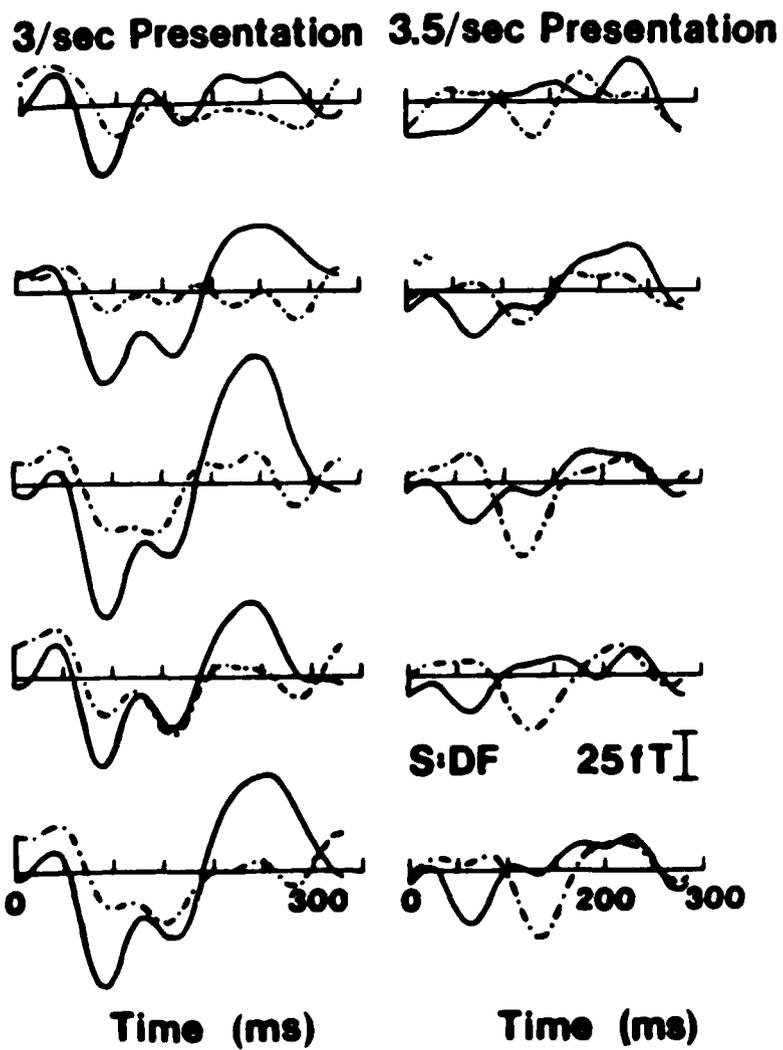


Figure 2

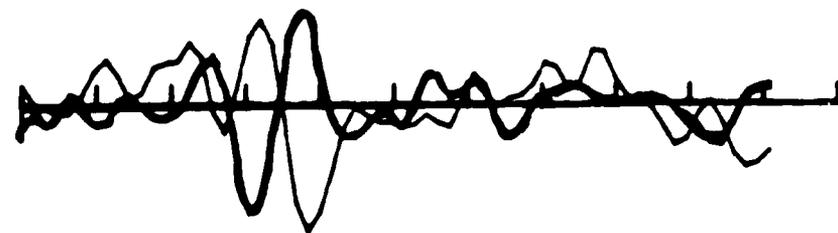
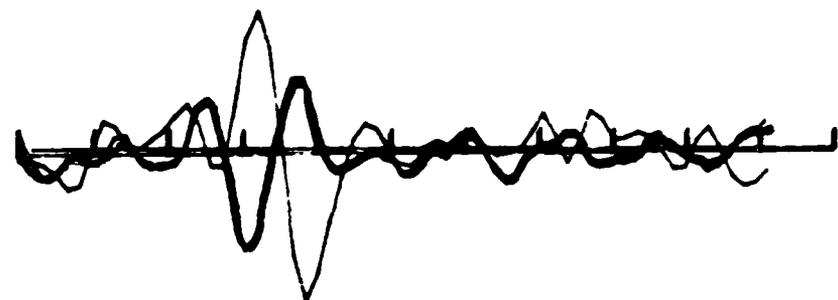
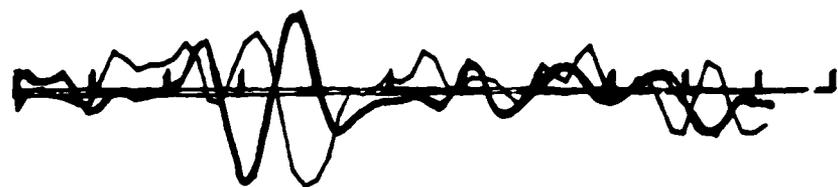
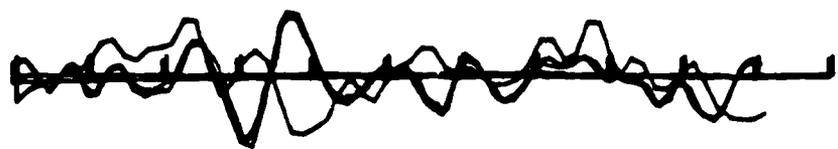


Figure 3

SV  
TRANSIENT

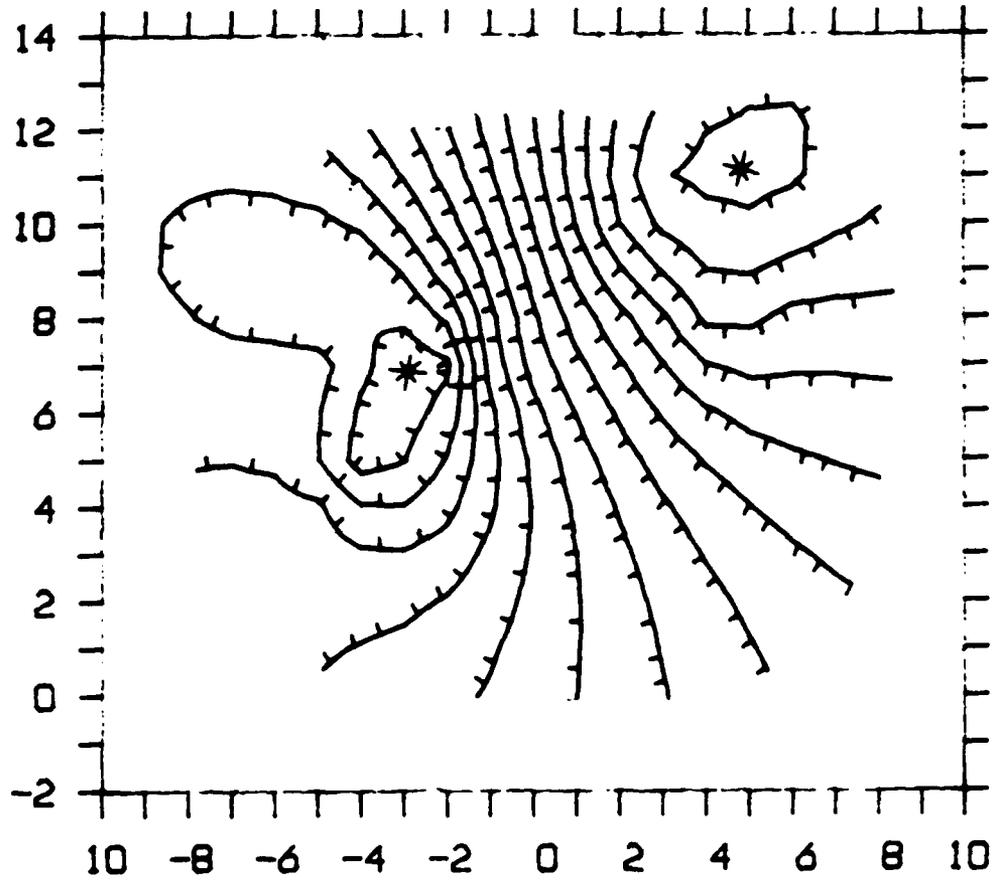


Figure 4

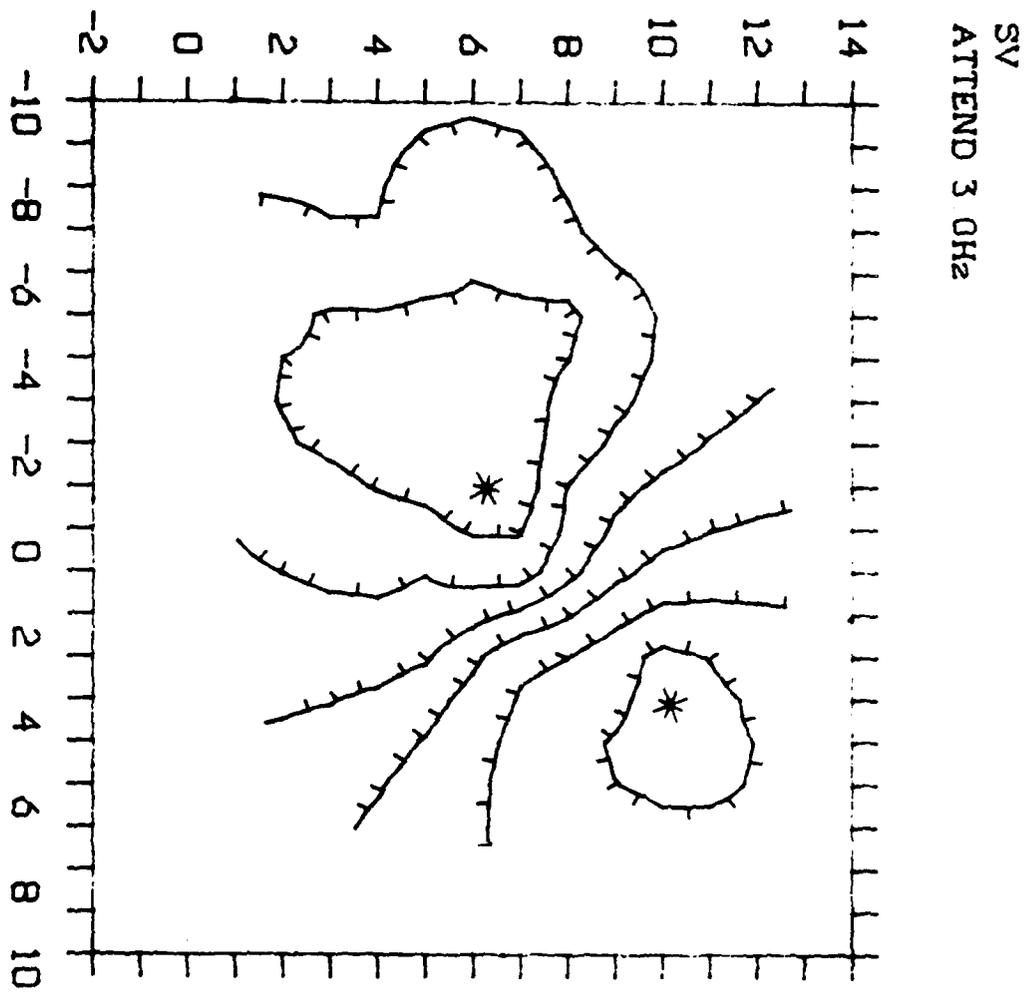


Figure 5a

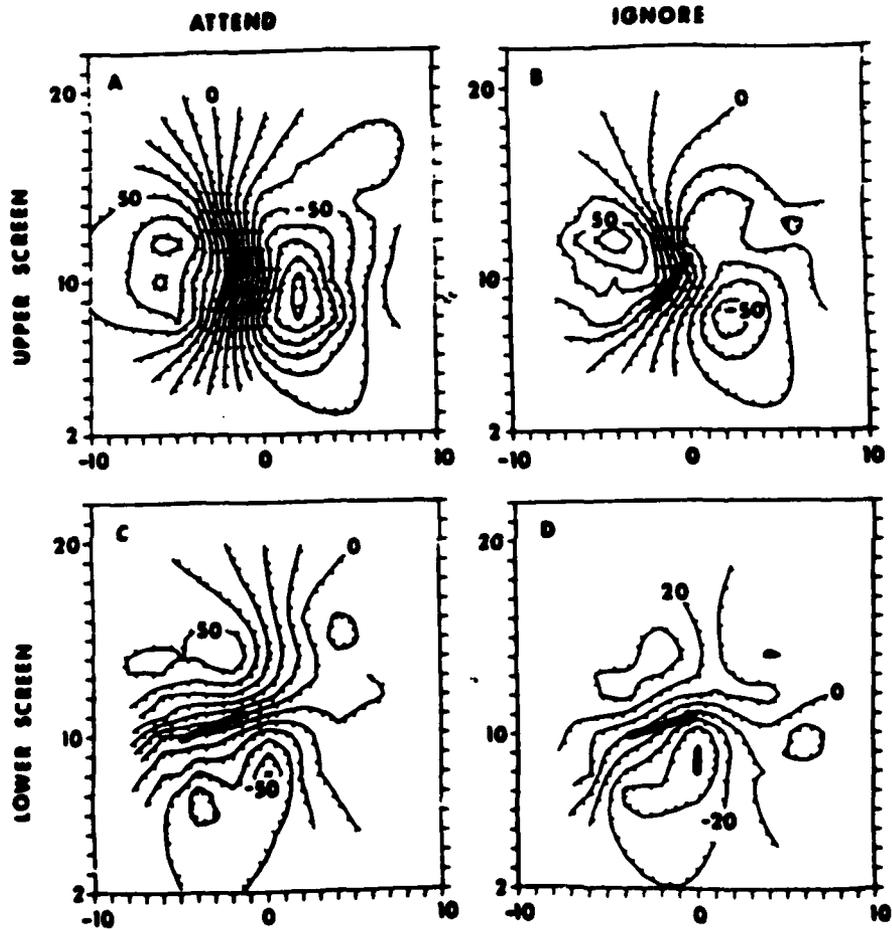


Figure 6

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