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EVOKED MAGNETIC FIELDS REVEAL DIFFERENT VISUAL AREAS IN HUMAN C--ETC(U)

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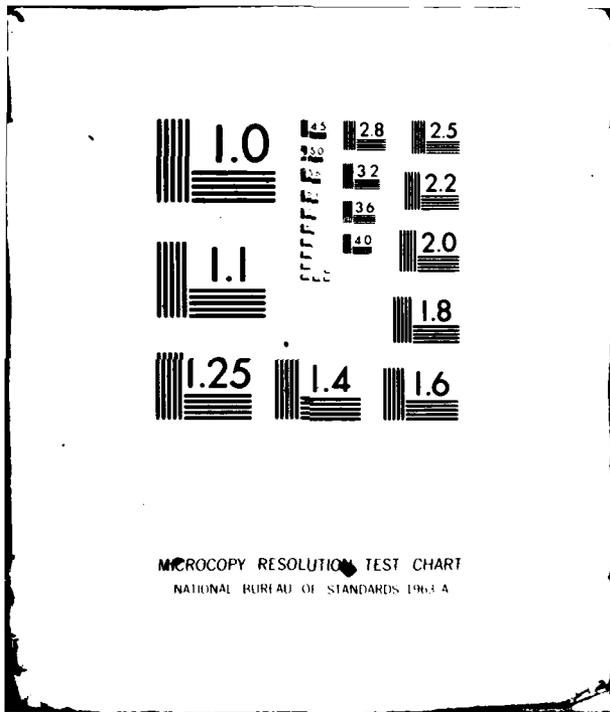
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Detailed maps of the patterns of steady state magnetic fields evoked by visual stimuli were constructed from measurements made over the occipital region of the head. The maps indicate the presence of at least two, and for some subjects three, current sources having different response properties, e.g., differing relationships between the response latency and spatial frequency of the display.

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EVOKED MAGNETIC FIELDS REVEAL DIFFERENT VISUAL AREAS IN HUMAN
CORTEX *

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Introduction

The classic method for studying the gross electrical activity of the human brain is to measure the differences in electrical potential between electrodes attached to the scalp. These potential differences develop as a result of volume currents that spread out from their source in active neural tissue throughout the conductive media of the head. This method has now been supplemented by one in which superconducting devices with sufficient sensitivity are employed to detect magnetic fields outside the head (1). These fields are associated with current flowing within the cortex. Theoretical considerations as well as empirical evidence point to the fact that these two methods, the method of measuring potentials and the method of measuring fields, provide complementary information despite the fact that both phenomena probably have common sources.

As Okada et al. (2,3) point out in this conference, the somatic evoked field is similar to the somatic evoked potential when measured at the surface of the cortex. In experiments performed by Goff et al. (4) it was found that the pial response -- the response measured between an electrode on the surface of the cortex and linked earlobes -- falls off rapidly when the active electrode is moved a short distance from the known site of neural activity in the vicinity of the

Rolandic fissure. When the somatic evoked potential is measured at the scalp the response is relatively unaffected by moving the active electrode over much larger distances. This difference between the pial and scalp recordings is no doubt due to the fact that the intervening media -- cerebral spinal fluids, the dura, and the skull and the skin -- smear the volume currents. One consequence of this is that the electrode on the scalp "sees" the superimposed activity of many sources, even some distant from the site of recordings. Moreover, the so-called "inactive" electrode is not truly indifferent and it makes an unknown contribution to the recorded response.

The widespread volume and skin currents that produce the scalp recorded evoked response could not be major contributors to the detected magnetic field. The reason for this is that small changes in the position of the pickup coil result in a large variation in response magnitude. This variation is similar to what is seen in the pial recordings but not in the scalp recordings. Apparently, the current density in the region giving rise to the large pial potentials is sufficiently great to produce detectable fields outside the head. We may assume from the similar behavior of the pial and external field recordings that the intervening media are transparent to the field and that the field measurements are in many ways equivalent to the electrical study of the exposed brain.

This conclusion is strongly supported by the apparently high degree of spatial resolution afforded by magnetic recordings. For example, stimulating the little finger produces a field pattern about the head similar to that which would be produced by a current dipole oriented orthogonally to the Rolandic fissure. Brenner et al. (5) found that they could localize this equivalent current dipole to within 1 cm. Very similar field pattern is produced by stimulation of the thumb of the same hand. However, the hypothetical equivalent current dipole that would produce the thumb's field was

located 2 cm lower on the head along the Rolandic fissure. Okada *et al.* (2) report similar resolution for the transient field evoked by median nerve stimulation. Such resolution has not been attained with conventional electrodes attached to the scalp.

The auditory evoked field is another source of evidence for the assertion that the magnetic method provides a high degree of spatial resolution. The auditory evoked field is sharply localized in the vicinity of the Sylvian fissure, the site of the auditory projection areas (6). The auditory evoked potential is strongest when the active electrode is located at the vertex and it is quite strongly represented at many locations about the head.

One limitation of magnetic field measurements follows from the fact that they do afford so high a degree of spatial resolution. Unlike evoked potential recordings, the magnetic recordings show no sign of far-field effects such as responses that arise in the brain stem a few milliseconds after sensory stimulation. Such far-field effects are undoubtedly due to the weak volume currents that spread out from distant sources. While these are sufficient to produce detectable potential differences at the scalp, their local brain stem current is too deep inside the head to produce a detectable magnetic field. In addition, the symmetry of the volume currents may well produce a vanishingly small net magnetic field.

In view of the resolution that is possible in recording from the somatic and auditory systems, it is of some interest to determine if that resolution makes it possible to obtain useful information about the human visual cortex. The visual cortex is a complex structure composed of several different areas. These areas occupy relatively large portions of the primate brain and the visual field is fully mapped onto several of them. Consequently, given a high degree of spatial resolution in the detecting system it may well be possible

ultimately to separately study the activity of these visual areas in response to diverse kinds of visual stimuli. This capability, if possible, may have important applications in clinical neurology.

With this motivation in mind, we measured the visually evoked magnetic field in some detail -- studying how it varies with the position of the 2.3 cm diameter pickup coil over the scalp as well as with the properties of the stimulus.

Our data suggest that it is possible to detect different "visual areas". Maps of the responses obtained at various positions in the posterior portions of the head indicate the presence of more than one source and, moreover, the recorded responses differ as a function of stimulus parameters. The data we obtained differed greatly among subjects but this is to be expected in view of the wide range of individual difference in cortical geometry. (7).

Methods

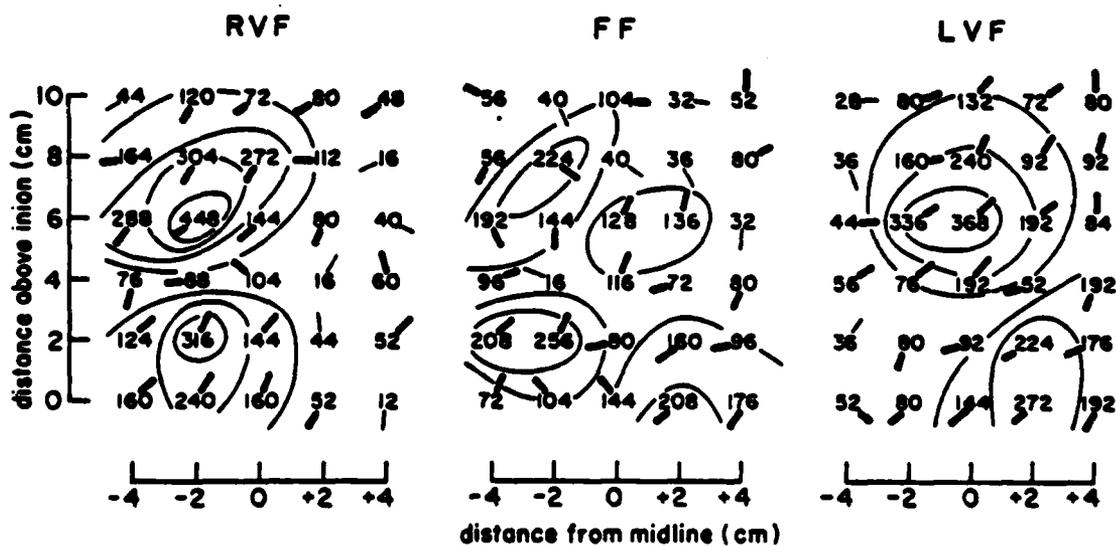
The stimuli were sinusoidal gratings generated on the face of a CRT and reversed temporally in contrast in a square wave fashion. Three viewing conditions were employed. These were produced by having the subject fixate the center of the 9 deg diameter display when it was filled with a grating pattern or when either the left or right halves of the grating were occluded. In the latter two cases this resulted in stimulation of either the left or right hemifields^{hemispheres} and, consequently, the left or right hemispheres of the brain. The spatial frequency of the grating employed here was 5 c/d, its contrast was 33%, and its average luminance was 52 cd/m².

Since the contrast reversal rate was 13 Hz, the detector (SQUID) output was filtered at 13 Hz before averaging to provide a steady state sinusoidal response which is completely

characterized by its amplitude and phase. The phase is measured from the stimulus to the maximum field directed out of the head.

Results and Discussion

Figure 1 contains maps of responses obtained from subject RL when he was stimulated by the left, right and full 9 deg visual display. The maps derived from left and right half-field stimulations are nearly symmetrical. Each contains two regions of strong responses located over the appropriate cerebral hemisphere. The orientations of the dark bars in the figure indicates the response phases. (The thin bars repre-



evoked field: femtotesla
 isochamp contours: 100,200,300,400 fT
 observer: RL

reversal rate = 13Hz
 spatial frequency = 5 c/d
 contrast = 33%
 luminance = 52 cd/m²

Figure 1. Visual responses recorded at various points about the scalp of subject RS for stimulation of the right visual field (on left), left visual field (on right), and full visual field (center). Solid lines are isochamps. The short lines indicate response phases; thin lines indicate responses at or near the noise level.

sent responses not significantly different from the level of the background noise.) The phases of the responses in the two regions from each hemisphere are approximately 180 deg apart. The appearance of the pattern and the reversal of phase suggests a current dipole model. This hypothetical dipole is located in the appropriate hemisphere for the stimulated visual field. To a first approximation, the full field response map is equal to the vector sum of the responses resulting from separate stimulation of the two half-fields.

The data are not completely described by two current dipoles, one in each hemisphere, as indicated by a careful analysis of the phases of the responses. It is necessary to consider the role of noise in this analysis. If the response consists of a signal from the brain and noise having half the amplitude of the signal, then, in the worst case, when the signal and noise are 90 deg out-of-phase, the resultant phase will differ by ± 27 deg. Now, if only one current source is responsible for the field in each hemisphere then the phases will be either in or 180° out-of-phase with each other. The data for the left and right visual stimuli contain responses whose phases differ from each other by amounts other than 180 degrees and which can not be explained on the basis of noise alone. For example, the phase at (0,4) in the right field map is 90 degrees out-of-phase relative to the maximum responses at (-2,-2) and (-2,6). The responses at their maxima are 8 to 10 times the noise level and the response at (2,4) 2.5 times the noise level. Therefore, at most noise can only be responsible for 29° of the 90 degree phase difference. Apparently, some other source is contributing to the response.

Figure 2 shows maps from a second subject (DB). The same stimuli were used. Instead of trying to construct isochamps (iso field strength lines) as in Figure 1, the left and right maps have been marked off into two groups of isophasic responses about 180 degrees apart.

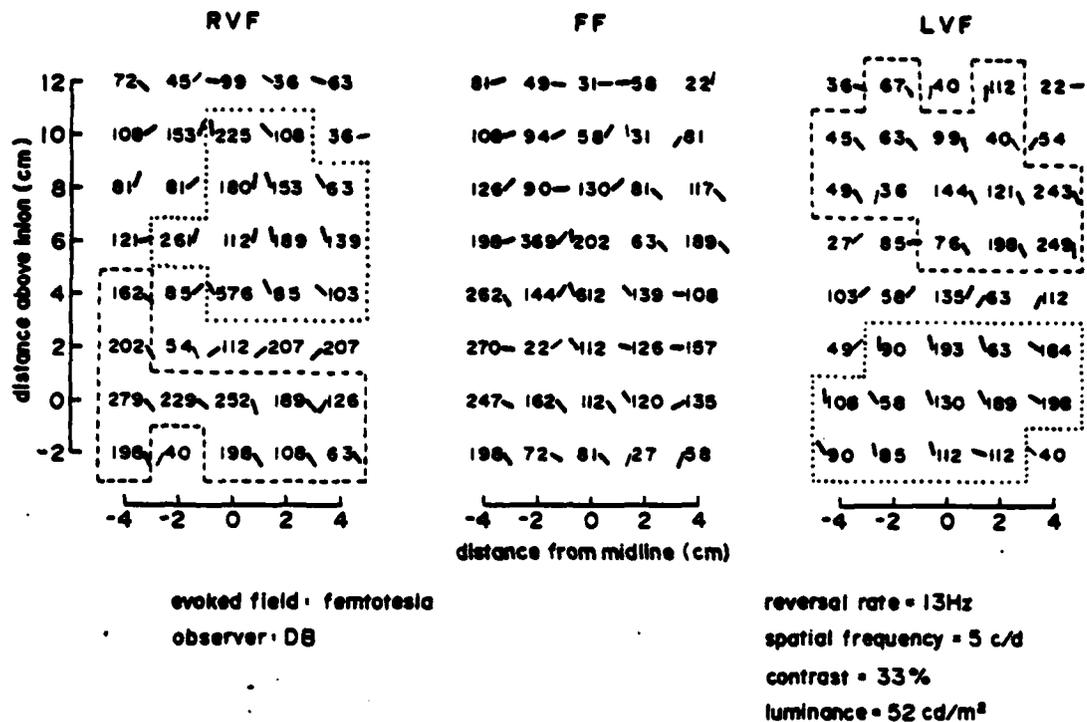


Figure 2. Visual responses recorded at various points about the scalp of subject DB for stimulation of right visual field (on left), left visual field (on right) and full visual field (center). Dashed and dotted lines enclose responses of approximately the same phase. The short lines indicate response phases; thin lines indicate responses at or near the noise level.

There are several responses that cannot be placed in either group. Their phases are about 90 degrees apart and some of them are 180 degrees out-of-phase with each other. For example, in the left field map, the responses (-4,4), (-2,4) and (0,4) are 180 degrees out-of-phase from the responses at (2,4) and (4,4) while all these responses are approximately 90 degrees out-of-phase from the responses grouped by the dotted and dashed lines. In the right visual field map, the responses at (0,2), (2,2) and (4,2) are 180 degrees out-of-phase relative to the responses at (-2,4), (-4,6), (-4,8), (-2,8) and other positions as well. Again, these responses are about 90 degrees out-of-phase from the responses within the isophasic regions.

The existence of multiple sources has been confirmed by studying the response phase variation as a function of stimulus parameters. For subject DB Figure 3a shows the phase versus reversal rate data recorded at position (0,4) for full-field stimuli. The full-field response recorded at position (0,4) is dominated by the activity of the left hemisphere. We previously reported that for a given spatial frequency and contrast, the response phase at this same position is proportional to reversal rate (stimulus frequency) over a range of from 8 to 20 Hz (8). Moreover, the slope of the function (latency) relating phase and stimulus frequency

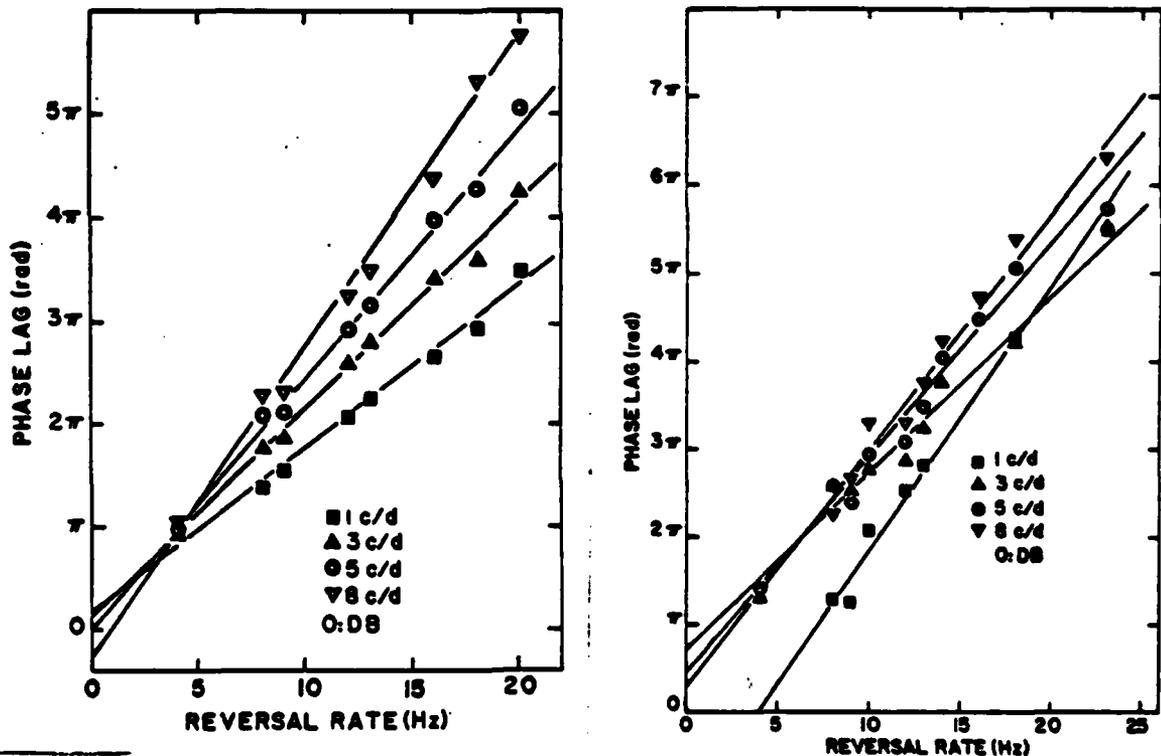


Figure 3. Phase of response versus stimulus reversal rate for stimuli at various spatial frequency measured at a) a point on the midline of the scalp of DB and 4 cm above the inion and b) on the midline and 9 cm above the inion.

increases monotonically with the spatial frequency of the pattern. The computed latencies of these responses correlate highly with a behavioral measure (simple reaction time) to grating presentation. Similar data have been obtained from several subjects.

Previous full field mapping studies with this subject showed an abrupt change in phase of 90 degrees as the probe was moved up the midline (Figure 4). This was verified with four different spatial frequencies. A similar shift is seen in the more complete full field map in Figure 2. Placing the probe at (0,9) and measuring the phase as a function of spatial and temporal frequencies results in the plots in Figure 3b. The phase versus reversal rate plots obtained for 3, 5 and 8 c/d gratings show an increase in latency with spatial frequency. The latency of the 5 and 8 c/d gratings are statistically the same at both positions (0,9) and (0,4) while they were different for the 1 and 3 c/d gratings

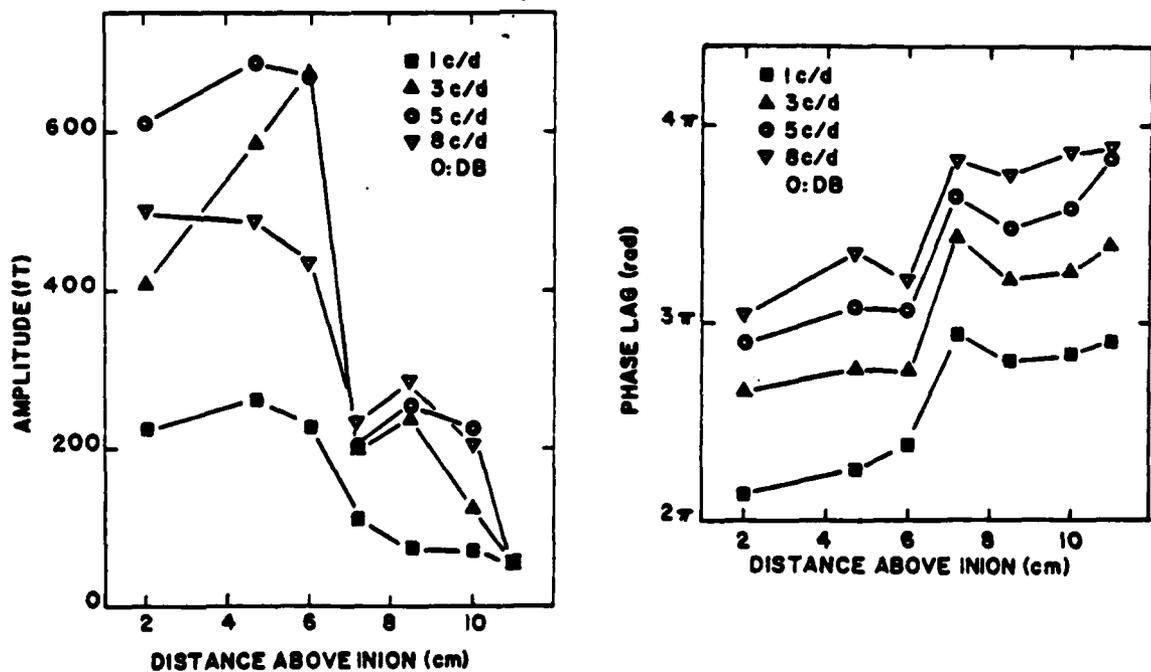


Figure 4. a) Amplitude and b) phase of responses for 4 different spatial frequencies at several positions along the midline of subject DB.

($\alpha = .01$). The latencies for the 1 c/d grating was 71 msec greater at the higher position; 25 msec greater for the 3 c/d grating at (0,9).

These differences in responses have been seen on another subject as well. Clearly, in these two subjects, two sets of active cells responding to the stimuli have been detected.

It should be noted (in Figures 1 and 2) that there is an approximate mirror symmetry of the responses obtained by stimulating the two half-fields. This symmetry is to be expected if current flow in the brain is symmetric with respect to the vertical midline. The remaining responses (those 90 degrees out-of-phase) ^{ALD} do not exhibit symmetry. ~~This might indicate that these responses are from a set of cells that respond when either hemisphere is being stimulated.~~

Since we now know that we can detect activity from at least two sets of cells, we can explain the phase variability seen within the isophasic regions in Figure 2. Since the detector is seeing activity from two sets of cells responding 90 degrees out-of-phase, the resultant phase and amplitude are determined by superposition of the fields from these two populations. If the populations are far enough apart, then one of them will predominate and the two populations can be studied independently.

Figure 5 shows field maps from another subject (PSR). His right visual field map is similar to that of Figure 1 and 2. It contains two main regions with phases 180 degrees apart and other responses with phases indicating other sources. However, responses to left field stimuli show no discernible pattern even though all responses for this subject are based on three one-minute averages. This difference between the left and right field responses suggests a large asymmetry in the geometry of the two hemispheres of this subject.

The responses from this subject are unlike anything seen previously. Measuring near (-3,5), the slopes for 5 different grating stimuli were all about equal, i.e., corresponding to a latency of about 125 msec (Figure 6).

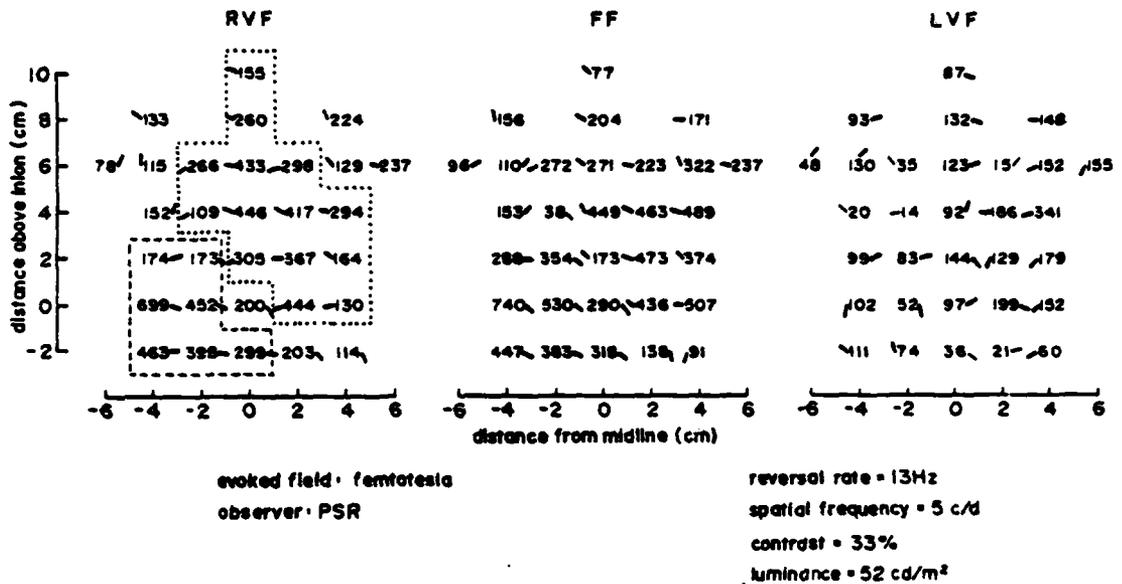


Figure 5. Visual responses recorded at various points about the scalp of subject PSR for stimulation of the left visual field (on right), right visual field (on left) and full field (center). Dashed and dotted lines enclose regions of approximately the same phase. Short lines indicate response phases; thin lines indicate responses at or near the noise level.

The stimuli used here were square wave gratings at 100% contrast and an average luminance of 66 cd/m². But the use of square wave gratings of high contrast cannot explain the difference in the responses. In another subject we obtained smooth variations in latency with both sine and square wave stimuli and with high and low contrast. Furthermore, sample data were collected with this subject (PSR) using 33% contrast sine wave gratings at an average luminance of 52 cd/m² and obtained behavior similar to that obtained with the square

wave gratings. At position (2.5, -3) responses were obtained using the sine wave gratings and these did show the monotonic increase in slope with spatial frequency.

Thus, we also detected two sets of cells responding to the stimuli in subject PSR. ⁴The set is similar to that seen in other subjects. The other set ⁴⁵has not, although preliminary data in a new subject suggests that some of his responses

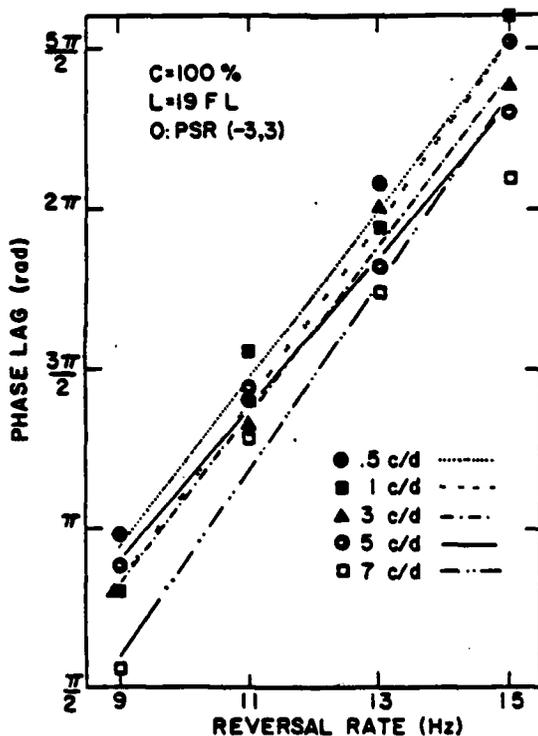


Figure 6. Phase of response versus stimulus reversal rate for stimuli at various spatial frequencies recorded at a location 3 cm above and 3 cm to the left of theinion of subject PSR.

show this behavior.

Conclusions

Because of the high spatial resolution possible with neuro-magnetic techniques, and because of anatomical differences across subjects, we seem to have detected at least three sets of cells that respond uniquely to contrast reversal gratings.

Of course, separate sets of cells are expected on the basis of extensive work on animals (9). But at this stage it is difficult to compare our responses with the single cell measurements obtained from animals. Evoked potentials from area 17 of the exposed cat cortex show increases in latency with spatial frequency (10). While this is suggestive, it is not sufficient for us to claim that our responses showing similar increases are from area 17 in humans.

Although our results pose many more questions than they answer, such as identifying the anatomical regions involved, they confirm our original proposal that it is possible to discretely detect functionally different regions of the visual cortex in man. The remaining questions concerning the anatomical regions associated with our data can only be answered by further study.

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